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1979 USAF SUMMER FACULTY RESEARCH PROGRAM

Research Report
Volume 2 of 3

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This Volume 2 of 3 volumes presents the final research reports of the 1979 Summer Faculty Research Program participants. The program designed to stimulate scientific and engineering interaction between university faculty members and technical personnel at the Air Force laboratories, centers, and divisions has four specific objectives:
(1) To develop the basis for continuing research of interest to the Air Force at the faculty member's institution.
(2) To further the research objectives of the Air Force.

(3) To stimulate continuing relations among faculty members and their peers in the Air Force.
(4) To enhance the research interests and capabilities of scientific and engineering educators.

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by

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1979 USAF/SCEEE SUMMER FACULTY RESEARCH PROGRAM

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1979 USAF/SCEEE SUMMER FACULTY RESEARCH PROGRAM

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FINAL REPORT

ELECTROMAGNETIC DIFFRACTION BY A NARROW SLIT IN AN IMPEDANCE SHEET--E-POLARIZATION

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ELECTROMAGNETIC DIFFRACTION BY A NARROW SLIT

IN AN IMPEDANCE SHEET--E-POLARIZATION

by

Donald F. Hanson

ABSTRACT

Composite materials have come into use lately in aircraft construction because of their high strength and low weight. This report examines the shielding effectiveness of a narrow slit in a composite material. This corresponds to a joint or seam between two composite panels. For low frequency incident fields, the composite can be effectively modelled as an infinitely thin impedance sheet. The literature on impedance sheets is reviewed and a general integral equation formulation for impedance sheets is described. Since only narrow slits (seams) are of practical interest, a quasi-static (low frequency) approach is developed. The solution to the problem is expressed as series of integrals of Chebyshev or Legendre polynomials. This gives preliminary results for this problem. Suggestions for further work are given which will make the results given here useful in engineering.

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I. INTRODUCTION

The Air Force has a vital interest protecting sensitive electronic equipment inside airplanes from electromagnetic pulse (EMP) penetration through composite skin panels. Composite skin panels are being used on airplanes today instead of aluminum because they are stronger and lighter than aluminum. Composite panels offer less shielding than conventional metal panels, however. Besides direct penetration (diffusion) through the composite panel walls, inadvertent penetration through seams, joints, and windows is possible.

The evaluation of the electrical (shielding) properties of composite materials has been studied by Casey (1976, 1977). For a graphite composite, he concludes that the electrical conductivity in the direction normal to the sheet surface is approximately zero. The tangential conductivity is anisotropic, but he shows that it can be satisfactorily modelled by an isotropic conductivity of approximately 1.5×10^4 mhos/meter (for graphite). He further shows that the graphite composite acts, in effect, like a low pass filter. This means that only lower frequencies usually need to be considered.

Because the frequencies of interest are low, a sheet of graphite composite material of thickness δ and effective tangential conductivity σ_t can be modelled by an infinitely thin sheet of sheet impedance $Z_s = 1/\sigma_t\delta$. Ohm's law requires that inside the sheet,

$$\vec{E}_{tan} = Z_s\vec{J}$$

where $\vec{E}_{tan}$ is the tangential component of electric field in Volts/meter and $\vec{J}$ is the sheet current in Amps per meter.

This report describes a method of solving for the deterioration of shielding due to slits (seams) in composite materials. This is done by solving for the quasi-static (low frequency) magnetic field diffracted by a slit in an impedance sheet. Only the E-polarization is studied. Three different electromagnetic concepts are involved in treating this problem. These are

(a) Low frequency or quasi-static techniques

(b) Impedance boundary conditions

and (c) Scattering by slits.

Previous efforts which combine these three topics have been few. Hurd (1979) has recently treated a similar problem for the H-polarization. He uses an impedance plane instead of an impedance sheet boundary condition. Impedance planes have a surface impedance boundary condition whereas impedance sheets have a jump discontinuity boundary condition. Kaden (1959, p. 212) uses a conformal transformation to find the penetration through a gap in a plane shield with finite conductivity and thickness. This work has been summarized by Butler, et al (1976).

The literature that describes one of the three subjects individually is reviewed briefly below.

(a) References on low-frequency techniques

Low frequency scattering techniques are often used because analytical solutions can sometimes be obtained. Two review articles on low frequency techniques have been written by Kleinman (1967, 1978). Quasi-static techniques reduce the dynamic electromagnetics problem to a static problem by making suitable low frequency approximations. Latham and Lee (1968) develop quasi-static boundary conditions for inductive shields by neglecting displacement currents. Standard techniques for solving statics problems can then be applied. Such techniques are detailed by Sneddon (1966), among others.

(b) References on impedance boundary conditions

Use of impedance sheet boundary conditions has been of recent interest. Harrington and Mautz (1975) use them to treat thin dielectric shells. Senior (1978) discusses them in connection with impedance half planes. Casey (1977) gives conditions under which composites can be modelled by impedance sheet boundary conditions. Babinet's principle for impedance boundary conditions has been given by Baum and Singaraju (1974), Lang (1973), and Senior (1977).

(c) References on scattering by slits

Scattering by slits in perfectly conducting planes has been studied exhaustively. Scattering by slits in finitely conducting planes or in impedance sheets has not received much attention. Slits in perfectly conducting planes have been studied by Clemmow (1966), Hongo (1972), Houlberg (1967), Nomura and Katsura (1957), Millar (1960), and Otsuki (1976), among others. Lam (1976) has studied the shielding effectiveness of seams or joints in perfectly conducting aircraft skins. Diffraction by slits or apertures in impedance planes has been treated by Neugebauer (1956), Zakharyev, Lemanski and Shcheglov (1970), and Hongo (1972). Neugebauer develops an approach to treating apertures in absorbing screens by using symmetry conditions. Zakharyev, et al, handle the case of a dipole antenna located in a slit in a finitely conducting plane. Finally, Hongo uses the Weber-Schafheitlin integral to formulate the problem of diffraction by a slit in a screen with a surface impedance. Apparently, no one has previously studied the problem of interest here--diffraction by a slit in an impedance sheet.

II. OBJECTIVES

The objective of this research is to find the H-field diffracted by a narrow slit in an impedance (composite) sheet. Equations which are functions of slit width and panel thickness and effective conductivity are to be developed and solved. The solutions can then be used to study the deterioration of shielding due to slits (seams) in composite panels. Three possibilities exist for each slit width and panel thickness and conductivity. One might find that penetration through the slit is the major component of coupling. On the other hand, one might find that penetration through the slit can be neglected compared to the direct penetration (diffusion) through the walls. Finally, it might turn out that both coupling through the slit and the walls has to be considered.

III. REFLECTION AND TRANSMISSION COEFFICIENTS OF AND THE CURRENT IN AN IMPEDANCE SHEET

The study of an impedance sheet without a slit will be a helpful start and of use later. Figure 1 shows an E-polarized plane wave incident upon an impedance sheet at an angle θ. The sheet is in the x=0 plane.

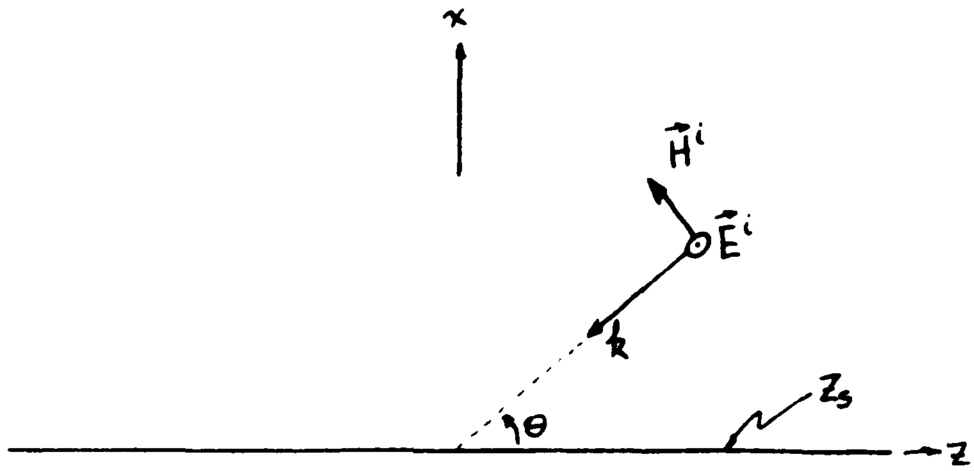

Figure 1. Plane wave incident on impedance sheet.

An $e^{-i\omega t}$ time dependence is assumed. The incident, reflected, and transmitted fields are denoted by superscripts i, r, and t, respectively. Let

$$\vec{k} = -k \sin\theta\,\hat{x} - k\cos\theta\,\hat{z} \qquad \vec{r} = x\hat{x} + z\hat{z} \qquad (3.1a,b)$$

then

$$\vec{H}^i = H_0 e^{i\vec{k}\cdot\vec{r}} (\hat{x}\cos\theta - \hat{z}\sin\theta) \qquad (3.2a)$$

$$\vec{E}^i = Z_0 H_0 e^{i\vec{k}\cdot\vec{r}}\,\hat{y} \qquad (3.2b)$$

$$\vec{H}^t = T H_0 e^{i\vec{k}\cdot\vec{r}} (\hat{x}\cos\theta - \hat{z}\sin\theta) \qquad (3.3a)$$

$$\vec{E}^t = T Z_0 H_0 e^{i\vec{k}\cdot\vec{r}}\,\hat{y} \qquad (3.3b)$$

Let

$$\vec{k}' = k\sin\theta\,\hat{x} - k\cos\theta\,\hat{z} \qquad (3.4)$$

then

$$\vec{H}^r = R' H_0 e^{i\vec{k}'\cdot\vec{r}} (\hat{x}\cos\theta + \hat{z}\sin\theta) \qquad (3.5a)$$

$$\vec{E}^r = R' Z_0 H_0 e^{i\vec{k}'\cdot\vec{r}}\,\hat{y} \tag{3.5b}$$

where $Z_0 = \sqrt{\mu_0/\varepsilon_0}$. There are two boundary conditions that must be satisfied across the impedance sheet [Casey (1977, p. 23)]. These are that $\vec{E}$ tangential ($\vec{E}_{tan}$) must be continuous and that

$$\vec{E}_{tan}(x=0) = Z_s \vec{J} = Z_s\left(\hat{x}\times\hat{z}\left[H_z(x=0^+) - H_z(x=0^-)\right]\right) \tag{3.6}$$

Applying these conditions, one obtains

$$1 + R' = T \tag{3.7}$$

$$\frac{Z_0}{\sin\theta}\,\frac{T}{Z_s} = 1 - R' - T \tag{3.8}$$

The reflection and transmission coefficients become

$$R' = \frac{-Z_0}{Z_0 + 2Z_s\sin\theta} \qquad T = \frac{2Z_s\sin\theta}{Z_0 + 2Z_s\sin\theta} \tag{3.9a,b}$$

The current in the sheet becomes

$$\vec{J} = \frac{\vec{E}_{tan}}{Z_s} = \frac{Z_0 H_0}{Z_s}\left(\frac{2Z_s\sin\theta}{Z_0 + 2Z_s\sin\theta}\right) e^{-ikz\cos\theta}\,\hat{y} \tag{3.10}$$

This current satisfies the integral equation

$$\frac{kZ_0}{4}\int_{-\infty}^{\infty} I(z')\,H_0^{(1)}(k|z-z'|)\,dz' + Z_s I(z) = Z_0 H_0 e^{-ikz\cos\theta} \tag{3.11}$$

as may be easily shown by a Fourier transformation.

IV. SLIT INTEGRAL EQUATIONS: DYNAMIC CASE

A standard approach for solving electromagnetics problems is the integral equation approach. Consider a two-dimensional slit of width 2b between two impedance sheets of impedances Z_{s_1} and Z_{s_2}, as shown in

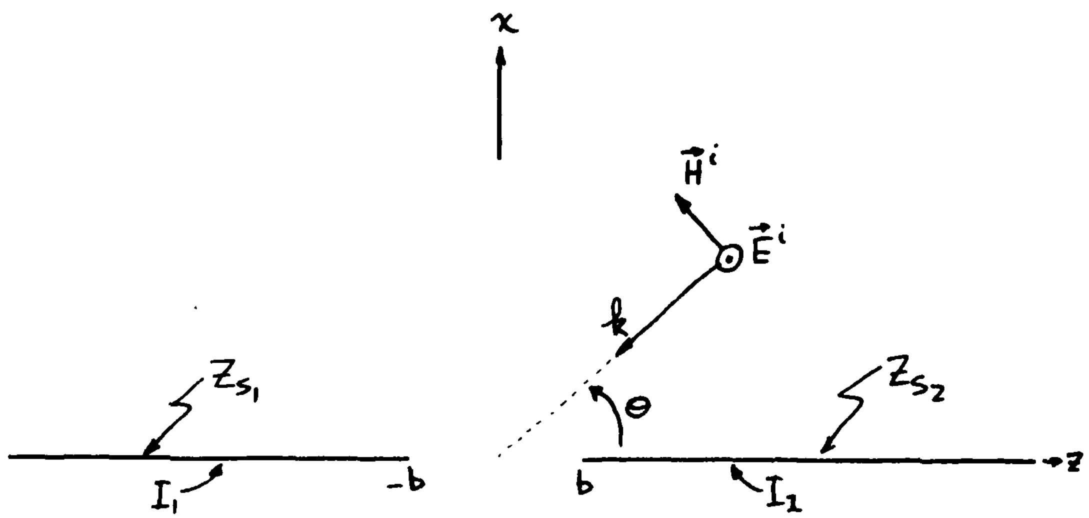

Figure 2. Dynamic plane wave incident on slit in impedance plane.

Figure 2. The vector potential for this problem is

$$\vec{A} = i\frac{\mu_0}{4}\hat{y}\int_{-\infty}^{-b} I_1(z')H_0^{(1)}\left(k\sqrt{x^2+(z-z')^2}\right)dz'$$

$$+\; i\frac{\mu_0}{4}\hat{y}\int_{b}^{\infty} I_2(z')H_0^{(1)}\left(k\sqrt{x^2+(z-z')^2}\right)dz' \qquad (4.1)$$

The electric field scattered by the impedance sheets is given by

$$\vec{E}^s = i\omega\vec{A} \qquad (4.2)$$

Since the total electric field is equal to the incident field plus the scattered field and is also equal to $Z_{s_1} I_1$ over $-\infty < z < -b$ and to $Z_{s_2} I_2$ over $b < z < \infty$, both for $x=0$, one obtains the coupled integral equations

$$Z_0 H_0 e^{-ikz\cos\theta} - \frac{kZ_0}{4}\int_{-\infty}^{-b} I_1(z') H_0^{(1)}(k|z-z'|)dz'$$

$$- \frac{kZ_0}{4}\int_{b}^{\infty} I_2(z') H_0^{(1)}(k|z-z'|)dz' = Z_{s_1} I_1(z) \qquad (4.3a)$$

$$z < -b$$

$$Z_0 H_0 e^{-ikz\cos\theta} - \frac{kZ_0}{4}\int_{-\infty}^{-b} I_1(z') H_0^{(1)}(k|z-z'|)dz'$$

$$- \frac{kZ_0}{4}\int_{b}^{\infty} I_2(z') H_0^{(1)}(k|z-z'|)dz' = Z_{s_2} I_2(z) \qquad (4.3b)$$

$$z > b$$

These equations can be solved by using numerical techniques.

Since these equations are very complicated, it is desirable to simplify them. One possibility would be to try using a Babinet's principle of the types described by Baum and Singaraju (1974), Lang (1973), or Senior (1977). Unfortunately, this does not lead to a significant simplification of the equations and so is not considered further. Another possibility is to look at the equations for low frequencies. This also does not lead to a major simplification in the equations as they stand because the currents are supported over two semi-infinite regions and

and are therefore not directly tenable to low frequency approximations. A solution can be found using this method, however, by solving for the difference between the actual currents and the currents that would be present without the slit. This perturbation current goes to zero as one gets away from the slit. This approach is the one taken here.

V. QUASI-STATIC FORMULATION OF THE SLIT PROBLEM

The problem that will be studied here is less general than the one detailed in the last section. First of all, it will be treated on a quasi-static basis. Secondly, only the case of normal incidence will be studied. Finally, both sides of the sheet have the same impedance. This is shown in Figure 3.

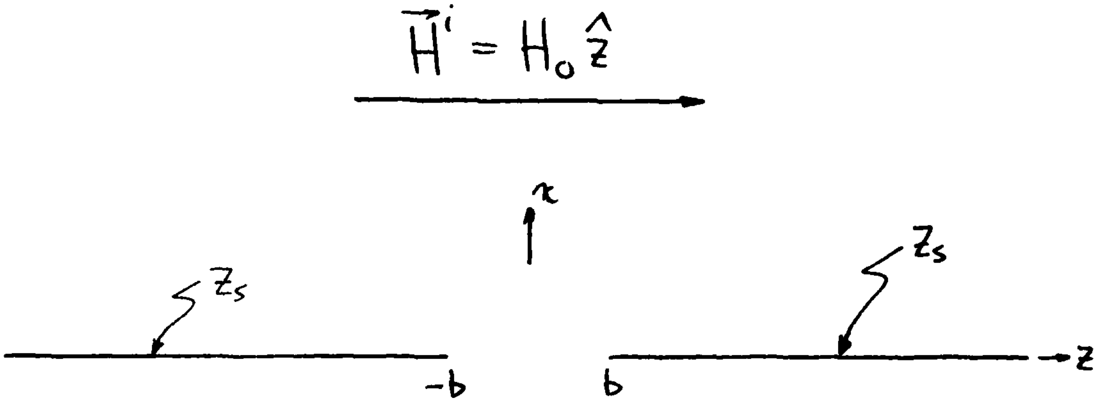

Figure 3. Quasi-static field incident on slit in impedance plane.

Let the incident field $\vec{H}^i = H_0\hat{z}$ be the field of a static current sheet of strength $2H_0\hat{y}$ located at infinity. It is of interest here to find the field above and below the impedance sheet and also in the gap. The basis for the quasi-static formulation used here is provided by Latham and Lee (1968). Maxwell's equations can be written as

$$\nabla \times \vec{H} = -i\omega\varepsilon\vec{E} + \vec{J} \tag{5.1}$$

$$\nabla \times \vec{E} = i\omega\mu \vec{H} \tag{5.2}$$

$$\nabla \cdot \vec{H} = 0 \qquad \nabla \cdot \vec{E} = 0 \tag{5.3a,b}$$

where

$$\vec{E}_{tan} = Z_s \vec{J} \tag{5.4}$$

Thus, these equations can be written as

$$\nabla \times \vec{H} = \vec{J} = \frac{\vec{E}_{tan}}{Z_s} \tag{5.5}$$

$$\nabla \times \vec{E} = i\omega\mu \vec{H} \tag{5.6}$$

provided that Z_s is small enough and the frequency is low enough so that the displacement current can be neglected. Off of the sheets, one has

$$\nabla \times \vec{H} = 0 \tag{5.7}$$

and

$$\nabla \cdot \vec{H} = 0 \tag{5.8}$$

The first condition implies that

$$\vec{H} = -\nabla\phi \tag{5.9}$$

where ϕ is the magnetic scalar potential [Stratton (1941), pp. 225-267] while the second gives that

$$\nabla^2\phi = 0 \tag{5.10}$$

away from the sheets. The incident potential is related to the incident field by

$$\vec{H}^i = -\nabla\phi^i \qquad (5.11)$$

so that

$$\phi^i = -H_o z . \qquad (5.12)$$

The arbitrary constant of integration is chosen to be zero so that $\phi^i(z=0) = 0$. This makes the incident potential an odd function--a property which will be very useful later.

It is now necessary to determine the boundary conditions which the potential must satisfy. Latham and Lee (1968) show that the surface divergence of $\vec{J}$ is zero, that is,

$$\nabla_s \cdot \vec{J} = 0 \qquad (5.13)$$

in the quasi-static case for an impedance sheet. Thus, the current can be written as

$$\vec{J} = \hat{x} \times \nabla_s \psi \qquad (5.14)$$

where ψ is a scalar function. This follows from equation 38, page 502 of Van Bladel (1964). Figure 4 shows the cross-secional view of the impedance sheet and a surface S of integration. Integrating equation (5.5)

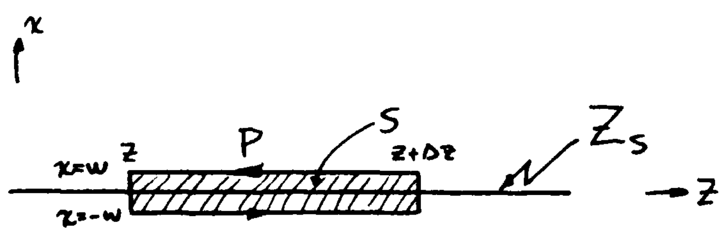

Figure 4. Surface and path of integration.

over the surface S gives

$$\int_S \nabla\times\vec{H}\cdot d\vec{S} = \oint_P \vec{H}\cdot d\vec{L} = \left[-H_z(0^+) + H_z(0^-)\right]\Delta z$$

$$= \int_S \vec{J}\cdot d\vec{S} = \left(-\nabla_s\psi\right)\Delta z \qquad (5.15)$$

After using (5.9), one obtains

$$\phi(0^+) - \phi(0^-) = -\psi. \qquad (5.16)$$

This relates the potential to ψ. Since $\mu\oint\vec{H}\cdot d\vec{S} = 0$ over a small "pillbox" enclosing the surface, normal $\vec{H}$ is continuous across the surface and

$$\left.\frac{\partial\phi}{\partial x}\right|_+ = \left.\frac{\partial\phi}{\partial x}\right|_- = \frac{\partial\phi}{\partial x} \qquad (5.17)$$

on the boundary. One last condition must be found. Latham and Lee (1968, p. 1749) show that

$$i\omega\mu H_x = \hat{x}\cdot\nabla_s\times\vec{E}_{tan} = \hat{x}\cdot\nabla_s\times\left(Z_s\vec{J}\right) \qquad (5.18)$$

so that

$$-i\omega\mu\,\hat{x}\cdot\nabla\phi = Z_s\,\hat{x}\cdot\left(\nabla_s\times\hat{x}\times\nabla_s\psi\right) \qquad (5.19)$$

Therefore, one has

$$-i\omega\mu\frac{\partial\phi}{\partial x} = Z_s\left(\nabla_s^2\psi\right) \qquad (5.20)$$

after using identity 37, page 502 of Van Bladel (1964). Eliminating ψ between this equation and (5.16), one arrives at the second boundary condition that must be satisfied, namely,

$$i\omega\mu \left.\frac{\partial\phi}{\partial x}\right|_0 = Z_s\left(\nabla_s^2\left(\phi(0^+,z) - \phi(0^-,z)\right)\right) \qquad (5.21)$$

One might expect that a canonical problem to test these boundary conditions would be that of scattering by an impedance sheet without a slit. This does not lead to any useful result, however. Instead, one can use the results of section III for normal incidence. Thus, for k=0 and $\theta = 90°$, one has that $\vec{H}^i = H_0\hat{z}$, $\vec{H}^t = TH_0\hat{z}$, and $\vec{H}^r = -R'H_0\hat{z}$ where $T = 2Z_s/(Z_0+2Z_s)$ and $R' = -Z_0/(Z_0+2Z_s)$. It can thus be assumed that for $\phi^i = -H_0 z$

$$\phi^t = -TH_0 z \quad \text{and} \quad \phi^r = -RH_0 z \qquad (5.22a,b)$$

where $R = -R'$. By using these reflected and transmitted potentials, one can formulate the problem in terms of a potential ϕ^s which will be significant only in the neighborhood of the slit. For convenience, define

$$\phi^s = \begin{cases} \phi_> & x>0 \\ \phi_< & x<0 \end{cases} \qquad (5.23)$$

This potential must satisfy Laplace's equation (5.10). Using separation of variables techniques and integrating over all possible separation constants, one can write

$$\phi_> = H_0\int_0^\infty F_1(\lambda)\sin\lambda z\, e^{-\lambda x}\frac{d\lambda}{\lambda} \qquad (5.24a)$$

$$\phi_< = H_0\int_0^\infty F_2(\lambda)\sin\lambda z\, e^{+\lambda x}\frac{d\lambda}{\lambda} \qquad (5.24b)$$

The total potential can be written as

$$\phi = \begin{cases} \phi^+ & x > 0 \\ \phi^- & x < 0 \end{cases} \tag{5.25}$$

where

$$\phi^+ = \phi_> + \phi^i + \phi^r \tag{5.26a}$$

and

$$\phi^- = \phi_< + \phi^t \tag{5.26b}$$

Applying the condition (5.17), one obtains

$$-F_1(\lambda) = +F_2(\lambda) = F(\lambda). \tag{5.27}$$

Substituting this, (5.24), (5.22) in (5.26), one arrives at

$$\phi^+ = H_0 \int_0^\infty F(\lambda) \sin \lambda z \, e^{-\lambda x} \frac{d\lambda}{\lambda} - H_0 z - R H_0 z \tag{5.28a}$$

$$\phi^- = H_0 \int_0^\infty F(\lambda) \sin \lambda z \, e^{+\lambda x} \frac{d\lambda}{\lambda} - T H_0 z \tag{5.28b}$$

It is now necessary to find $F(\lambda)$. To do this, the previously derived boundary condition (5.21) can be applied on the impedance sheet. In the slit, the magnetic scalar potential must be continuous. The application of these two conditions gives dual integral equations which can be solved for $F(\lambda)$. Application of the first condition gives

$$Z_s \frac{d^2}{dz^2}\left(\phi^+(0,z) - \phi^-(0,z)\right) = -i\omega\mu H_0 \int_0^\infty F(\lambda) \sin \lambda z \, d\lambda$$

$$z > b, \; z < -b \tag{5.29}$$

Direct differentiation of $\phi^+ - \phi^-$ in (5.29) leads to an intractable result. It can be shown that

$$\int_0^\infty F(\lambda)\sin\lambda z\, d\lambda = -\frac{d^2}{dz^2}\int_0^\infty F(\lambda)\sin\lambda z\,\frac{d\lambda}{\lambda^2} \qquad (5.30)$$

This gives

$$\frac{d^2}{dz^2}\left(Z_s\left[\phi^+(0,z) - \phi^-(0,z)\right] - i\omega\mu H_0\int_0^\infty F(\lambda)\sin\lambda z\,\frac{d\lambda}{\lambda^2}\right) = 0 \qquad (5.31)$$

or

$$Z_s\left(\phi^+(0,z) - \phi^-(0,z)\right) - i\omega\mu H_0\int_0^\infty F(\lambda)\sin\lambda z\,\frac{d\lambda}{\lambda^2} = Az + B \qquad (5.32)$$

where A and B are constants. The constant of integration B must be zero by symmetry considerations. Therefore, equation (5.29) becomes

$$\int_0^\infty F(\lambda)\left[\lambda^{-1} - \frac{i\omega\mu}{2Z_s}\lambda^{-2}\right]\sin\lambda z\, d\lambda = \left(\frac{A}{2H_0Z_s} + \frac{1+R-T}{2}\right)z \qquad |z| > b \qquad (5.33a)$$

Application of continuity in the slit gives

$$\int_0^\infty F(\lambda)\sin\lambda z\,\frac{d\lambda}{\lambda} = \left(\frac{1+R-T}{2}\right)z \qquad -b<z<b \qquad (5.33b)$$

These equations can be normalized into the ranges (0,1) and (1,∞) by making changes of variables and using symmetry. Doing this yields the dual integral equations

$$\int_0^\infty F\left(\frac{\eta}{b}\right)\left[1 - \frac{i\omega\mu b}{2Z_s}\frac{1}{\eta}\right]\sin\eta w \frac{d\eta}{\eta} = \tag{5.34a}$$

$$= \left(\frac{A}{2H_0 Z_s} + \frac{1+R-T}{2}\right) bw \qquad w>1$$

$$\int_0^\infty F\left(\frac{\eta}{b}\right)\sin\eta w \frac{d\eta}{\eta} = \left(\frac{1+R-T}{2}\right) bw \qquad 0\leq w<1 \tag{5.34b}$$

These equations can be solved by using techniques given by Sneddon (1966, p. 113). The solution of these equations is postponed one section. In the next section, the solution for $Z_s=0$, the perfectly conducting case, is found.

VI. QUASI-STATIC SOLUTION FOR A SLIT IN A PERFECTLY CONDUCTING PLANE

The problem of a slit in a perfectly conducting plane is of interest because for a typical graphite composite sheet, $Z_s = 0.045$ ohms. This means that one can consider $Z_s=0$ for some applications. Upon setting $Z_s=0$ in (5.29) and normalizing, one has the dual integral equations

$$\int_0^\infty F\left(\frac{\eta}{b}\right)\sin\eta w \frac{d\eta}{\eta} = bw \qquad 0\leq w<1 \tag{6.1a}$$

$$\int_0^\infty F\left(\frac{\eta}{b}\right)\sin\eta w \, d\eta = 0 \qquad w>1 \tag{6.1b}$$

A similar pair of equations is solved in another way by Clemmow (1966, p. 91). Let $A(\eta) = F(\eta/b)$. Then the solution to these dual integral equations is given by Sneddon (1966, p. 103) and is

$$A(n) = b\, J_1(n) \qquad (6.2)$$

This means that

$$F(\lambda) = b\, J_1(\lambda b) \qquad (6.3)$$

Substituting this in equation (5.28), one obtains

$$\phi = \begin{cases} H_0 b \int_0^{\infty} J_1(\lambda b) \sin \lambda z \, e^{-\lambda x} \frac{d\lambda}{\lambda} - 2 H_0 z & x > 0 \\ -H_0 b \int_0^{\infty} J_1(\lambda b) \sin \lambda z \, e^{+\lambda x} \frac{d\lambda}{\lambda} & x < 0 \end{cases} \qquad (6.4)$$

The H-field is given by equation (5.9).

$$H_x = -\frac{\partial \phi}{\partial x} \qquad H_z = -\frac{\partial \phi}{\partial z} \qquad (6.5)$$

Performing these differentiations yields the expressions

$$H_x = H_0 b \int_0^{\infty} J_1(\lambda b) \sin \lambda z \, e^{-\lambda |x|} d\lambda \qquad (6.6)$$

$$H_z = \begin{cases} 2H_0 - H_0 b \int_0^{\infty} J_1(\lambda b) \cos \lambda z \, e^{-\lambda x} d\lambda & x > 0 \\ H_0 b \int_0^{\infty} J_1(\lambda b) \cos \lambda z \, e^{\lambda x} d\lambda & x < 0 \end{cases} \qquad (6.7)$$

These expressions cannot, in general, be simplified any further in an obvious way. The special cases z=0 and x=0, however, are of interest. For z=0, one finds

$$H_x(x,0) = 0 \qquad (6.8)$$

$$H_z(x,0) = H_0\left(1 + \frac{x}{\sqrt{x^2+b^2}}\right) \qquad (6.9)$$

For x=0, the result is different for $-b < z < b$ and for $|z| > b$ since the integrals are the discontinuous integrals of Weber and Schafheitlin [Magnus, Oberhettinger, and Soni (1966), p. 99 and p. 425]. The expressions for the slit fields with x=0 are found to be

$$H_x(0,z) = \frac{H_0 z}{\sqrt{b^2 - z^2}} \qquad |z|<b \qquad (6.10)$$

$$H_z(0,z) = H_0 \qquad |z|<b \qquad (6.11)$$

Those for the fields next to the conductor are

$$H_x(0,z) = 0 \qquad |z|>b \qquad (6.12)$$

$$H_z(x=0^+,z) = 2H_0 + \frac{H_0 b^2}{\sqrt{z^2-b^2}\left(|z| + \sqrt{z^2-b^2}\right)} \qquad |z|>b \qquad (6.13)$$

$$H_z(x=0^-, z) = \frac{-H_o b^2}{\sqrt{z^2-b^2}\left(|z| + \sqrt{z^2-b^2}\right)} \qquad |z|>b \qquad (6.14)$$

The equivalent current in the conductor can be written as

$$J_y = -2 H_o \frac{|z|}{\sqrt{z^2-b^2}} \qquad |z|>b \qquad (6.15)$$

VII. QUASI-STATIC SOLUTION FOR A SLIT IN AN IMPEDANCE SHEET

Formulas for the coupling through a slit of width 2b in a composite material modelled by an impedance sheet are found here. The dual integral equations which must be solved are given by equations (5.34). By using the fact that $\sin(z) = (\pi z/2)^{1/2} J_{1/2}(z)$, these equations become

$$\int_0^\infty B(\eta)\, J_{\frac{1}{2}}(\eta w)\, d\eta = \sqrt{\frac{2}{\pi}}\left(\frac{1+R-T}{2}\right) b\,(bw)^{\frac{1}{2}} \qquad (7.1a)$$

$$0 \le w < 1$$

$$\int_0^\infty B(\eta)\left[1 - \frac{i\omega\mu}{2Z_s}\frac{b}{\eta}\right] J_{\frac{1}{2}}(\eta w)\, d\eta =$$

$$= \sqrt{\frac{2}{\pi}}\left(\frac{A}{2H_o Z_s} + \frac{1+R-T}{2}\right) b\,(bw)^{\frac{1}{2}} \qquad (7.1b)$$

$$w > 1$$

where $B(\eta) = (\eta/b)^{-1/2} F(\eta/b)$. These equations are in the same form as (4.6.42) and (4.6.43) on page 113 of Sneddon (1966) with $\alpha=0$, $\nu=1/2$,

$$n(u) = \frac{-i\omega\mu}{2Z_s}\frac{b}{u} \qquad (7.2)$$

$$F(x) = \sqrt{\frac{2}{\pi}}\left(\frac{1+R-T}{2}\right) b\,(bx)^{\frac{1}{2}} \tag{7.3}$$

$$G(x) = \sqrt{\frac{2}{\pi}}\left(\frac{A}{2H_0 Z_s} + \frac{1+R-T}{2}\right) b\,(bx)^{\frac{1}{2}} \tag{7.4}$$

The solution for B(u) can be written in the form

$$B(u) = \sqrt{\frac{2}{\pi}}\left(\frac{1+R-T}{2}\right) b^{3/2}\, J_{3/2}(u) \; + $$

$$+ \; u\int_1^{\infty} t^{\frac{1}{2}}\, J_{\frac{1}{2}}(ut)\, g(t)\, dt \tag{7.5}$$

where g(t) is the solution of the integral equation

$$g(t) - \frac{\omega\mu}{2\pi Z_s}\, b\int_1^{\infty} g(u)\, \ln\left|\frac{t+u}{t-u}\right| du = Q(t) \qquad t>1 \tag{7.6}$$

The forcing function Q(t) is

$$Q(t) = \sqrt{\frac{2}{\pi}}\left(\frac{A}{2H_0 Z_s} + \frac{1+R-T}{2}\right) b^{3/2}\, t \; +$$

$$+ \; \frac{\omega\mu\, b^{5/2}}{2\pi Z_s}\sqrt{\frac{2}{\pi}}\left(\frac{1+R-T}{2}\right)\left\{ t - \left(\frac{t^2-1}{2}\right)\ln\left|\frac{t+1}{t-1}\right| \right\} \tag{7.7}$$

The unknown constant A can be found by requiring that Q(t) be bounded as $t \to \infty$. Therefore,

$$A = -2H_0 Z_s \left(\frac{1+R-T}{2}\right) \tag{7.8}$$

This is true because the second part of Q(t) behaves like 1/t as $t \to \infty$. This means that the right-hand side of (7.1b) and G(x) of (7.4) are zero. The integral equation for g(t) becomes

$$\frac{2\pi Z_s}{ikZ_0 b}\, g(t) - \int_1^\infty g(u) \ln\left|\frac{t+u}{t-u}\right| du =$$

$$= b^{3/2}\sqrt{\frac{2}{\pi}}\left(\frac{1+R-T}{2}\right)\left\{t - \left(\frac{t^2-1}{2}\right)\ln\left|\frac{t+1}{t-1}\right|\right\} \tag{7.9}$$

The right-hand side and the kernel of this equation can be expressed in terms of Legendre polynomials of the second kind $\mathcal{D}_n(t)$ as given by Magnus, Oberhettinger, and Soni (1966, p. 176). The kernel and t-dependence of the right-hand side can be written as $2\mathcal{D}_0(u/t)$ and $2(\mathcal{D}_0(t) - \mathcal{D}_2(t))/3$, respectively. Thus, equation (7.9) can also be written as

$$\frac{\pi Z_s}{ikZ_0 b}\, g(t) - \int_1^\infty g(u)\, \mathcal{D}_0\left(\frac{u}{t}\right) du =$$

$$= b^{3/2}\sqrt{\frac{2}{\pi}}\left(\frac{1+R-T}{6}\right)\left(\mathcal{D}_0(t) - \mathcal{D}_2(t)\right) \qquad t > 1 \tag{7.10}$$

Although this appears to be in a simple form, it apparently does not have a simple solution.

It does not appear that a series of Bessel functions can be used to conveniently solve equation (7.9). The use of orthogonal polynomials, however, does offer a convenient solution procedure. This means, however, that the support of the equation must be transformed to the interval (-1,1).

By using symmetry and two changes of variables, one obtains the equation

$$\frac{2\pi Z_s}{ikZ_0 b}\, g\left(\frac{1}{s}\right) + \int_{-1}^{1} \frac{1}{v^2}\, g\left(\frac{1}{v}\right) \ln|s-v|\, dv =$$

$$= b^{3/2}\sqrt{\frac{2}{\pi}}\left(\frac{1+R-T}{2}\right)\frac{1}{s^2}\left\{ s + \frac{s^2-1}{2}\ln\left|\frac{1+s}{1-s}\right|\right\} \qquad (7.11)$$

Let $h(t) = t^{-2}\, g(1/t)$. Then the above equation becomes

$$\frac{2\pi Z_s}{ikZ_0 b}\, s^2 h(s) + \int_{-1}^{1} h(v) \ln|s-v|\, dv =$$

$$= b^{3/2}\sqrt{\frac{2}{\pi}}\left(\frac{1+R-T}{2}\right)\frac{1}{s^2}\left\{ s + \frac{s^2-1}{2}\ln\left|\frac{1+s}{1-s}\right|\right\} \qquad (7.12)$$

It should be noted that the right-hand side can be expressed as a power series.

$$\frac{1}{t^2}\left\{ t + \frac{t^2-1}{2}\ln\left|\frac{1+t}{1-t}\right|\right\} = 2\sum_{n=0}^{\infty}\frac{t^{2n+1}}{(2n+1)(2n+3)} \qquad (7.13)$$

It can also be expanded in Chebyshev polynomials $T_n(x)$. Since

$$t^{2n+1} = 2^{-2n}\sum_{p=0}^{n}\binom{2n+1}{p} T_{2(n-p)+1}(t) \qquad (7.14)$$

and

$$\sum_{n=0}^{\infty} a(n) \sum_{k=0}^{n} b(n,k)\, f(n-k,t) =$$

$$= \sum_{\ell=0}^{\infty} f(\ell,t)\left[\sum_{m=\ell}^{\infty} a(m)\, b(m, m-\ell)\right] \qquad (7.15)$$

one obtains

$$\frac{1}{t^2}\left\{t + \frac{t^2-1}{2}\ln\left|\frac{1+t}{1-t}\right|\right\} = \sum_{k=0}^{\infty} c_k\, T_{2k+1}(t) \qquad (7.16)$$

where

$$c_k = \sum_{m=k}^{\infty} \frac{2^{-2m}}{(2m+1)(2m+3)} \frac{(2m+1)!}{(m-k)!\,(m+k+1)!} \qquad (7.17)$$

The right-hand side can be expanded in Legendre polynomials of the first kind in a similar way. The result is

$$\frac{1}{t^2}\left\{t + \frac{t^2-1}{2}\ln\left|\frac{1+t}{1-t}\right|\right\} = \sum_{n=1}^{\infty} d_n\, P_{2n-1}(t) \qquad (7.18)$$

where

$$d_n = \sum_{m=n-1}^{\infty} \frac{(2m+1)!\,(m+n+1)!\,(2n-\frac{1}{2})\,2^{2n+2}}{(2m+1)(2m+3)\left[2(m+n+1)\right]!\,(m-n+1)!} \qquad (7.19)$$

The solution of equation (7.12) is first found in terms of a Chebyshev polynomial expansion. It is then solved by using a Legendre expansion.

(a) Solution of (7.12) by Chebyshev Series

Coefficients of a Chebyshev series which is a solution to (7.12) are found here. An interesting integral involving Chebyshev polynomials has been evaluated by Butler and Wilton (1979) and is

$$\int_{-1}^{1} \frac{T_n(u)}{\sqrt{1-u^2}} \ln|x-u|\, du = \begin{cases} -\pi \ln 2 & n=0 \\ -\frac{\pi}{n} T_n(x) & n>0 \end{cases} \qquad (7.20)$$

For convenience, a solution to (7.12) is assumed to be

$$h(t) = (1-t^2)^{-\frac{1}{2}} \sum_{k=0}^{\infty} a_k T_{2k+1}(t). \qquad (7.21)$$

Substituting this in (7.12), one obtains

$$-\pi \sum_{k=0}^{\infty} a_k \frac{T_{2k+1}(s)}{2k+1} + \frac{2\pi Z_s}{ikZ_0 b} \frac{s^2}{\sqrt{1-s^2}} \sum_{k=0}^{\infty} a_k T_{2k+1}(s) =$$

$$= b^{3/2} \sqrt{\frac{2}{\pi}} \left(\frac{1+R-\Gamma}{2} \right) \sum_{k=0}^{\infty} c_k T_{2k+1}(s) \qquad (7.22)$$

It can be shown that

$$\frac{t^2}{\sqrt{1-t^2}} = \sum_{\ell=0}^{\infty} \frac{(2\ell)!}{2^{2\ell}(\ell!)^2} \, 2^{-2\ell-1} \sum_{m=0}^{\ell+1} \frac{(2\ell+2)!}{m!(2\ell+2-m)!} T_{2(\ell-m)+2}(t) \qquad (7.23)$$

Since

$$\sum_{\ell=0}^{\infty} a(\ell) \sum_{m=0}^{\ell+1} b(\ell+1, m) f(\ell-m+1, t) =$$

$$= f(0,t) \left(\sum_{k=0}^{\infty} a(k) b(k+1, k+1) \right) +$$

$$+ \sum_{n=1}^{\infty} f(n,t) \left(\sum_{k=n-1}^{\infty} a(k) b(k+1, k+1-n) \right) \qquad (7.24)$$

It can be shown that

$$\frac{t^2}{\sqrt{1-t^2}} = \sum_{n=0}^{\infty} e_n T_{2n}(t) \tag{7.25}$$

where

$$e_0 = \sum_{k=0}^{\infty} \left(\frac{(2k)!}{2^{2k}(k!)^2 2^{2k+1}} \cdot \frac{[2(k+1)]!}{(k+1)!(k+1)!} \right) \tag{7.26a}$$

$$e_n = \sum_{k=n-1}^{\infty} \left(\frac{(2k)!}{2^{2k}(k!)^2 2^{2k+1}} \cdot \frac{[2(k+1)]!}{(k+1-n)!(k+n+1)!} \right) \tag{7.26b}$$

The second term in (7.22) is now proportional to

$$\left(\sum_{n=0}^{\infty} e_n T_{2n}(s) \right) \left(\sum_{k=0}^{\infty} a_k T_{2k+1}(s) \right) \tag{7.27}$$

After using the identity

$$T_{2k+1}(t)\, T_{2n}(t) = \frac{1}{2}\left[T_{2k+2\ell+1}(t) + T_{|2(k-\ell)+1|}(t) \right] \tag{7.28}$$

and collecting terms, one obtains

$$\left(\sum_{n=0}^{\infty} e_n T_{2n}(s) \right) \left(\sum_{k=0}^{\infty} a_k T_{2k+1}(s) \right) = \sum_{k=0}^{\infty} f_k T_{2k+1}(s) \tag{7.29}$$

where

$$f_k = \sum_{j=0}^{\infty} a_j \left(\frac{e_{|k-j|}}{\epsilon_{|k-j|}} + \frac{e_{j+k+1}}{2} \right) \tag{7.30}$$

and

$$\epsilon_0 = 1 \ , \qquad \epsilon_n = 2 \qquad n > 0 \tag{7.31}$$

Substituting these results in (7.22), one obtains

$$-\pi \sum_{k=0}^{\infty} \frac{a_k}{2k+1} T_{2k+1}(s) + \frac{2\pi Z_s}{i k Z_0 b} \sum_{k=0}^{\infty} f_k T_{2k+1}(s) =$$

$$= b^{3/2} \sqrt{\frac{2}{\pi}} \left(\frac{1+R-T}{2} \right) \sum_{k=0}^{\infty} c_k T_{2k+1}(s) \tag{7.32}$$

Collecting Chebyshev polynomials of the same order, one finds that

$$-\pi \frac{a_k}{2k+1} + \frac{2\pi Z_s}{i k Z_0 b} \sum_{j=0}^{\infty} a_j \left(\frac{e_{|k-j|}}{\epsilon_{|k-j|}} + \frac{e_{j+k+1}}{2} \right) =$$

$$= b^{3/2} \sqrt{\frac{2}{\pi}} \left(\frac{1+R-T}{2} \right) c_k \qquad k = 0, 1, 2, \cdots, \infty \tag{7.33}$$

Here, c_k is given by (7.17) and e_k is given by (7.26). This represents an infinite number of equations in an infinite number of unknowns a_k except when $Z_s=0$. By truncating the series appropriately, an approximate solution for the a_k can be found. The solution is just

$$h(t) = (1-t^2)^{-\frac{1}{2}} \sum_{k=0}^{\infty} a_k T_{2k+1}(t) \tag{7.34}$$

Recall that $h(t) = t^{-2} g(1/t)$. This means that $g(t) = t^{-2} h(1/t)$ and so

$$g(t) = \frac{1}{|t|\sqrt{t^2-1}} \sum_{k=0}^{\infty} a_k T_{2k+1}\left(\frac{1}{t}\right) \qquad (7.35)$$

Thus, substituting this in (7.5) gives the result

$$B(u) = \sqrt{\frac{2}{\pi}}\left(\frac{1+R-T}{2}\right) b^{3/2} J_{3/2}(u) \; +$$

$$+ \sqrt{\frac{2}{\pi}} \sqrt{u} \sum_{k=0}^{\infty} a_k \int_1^{\infty} \frac{\sin ut}{t\sqrt{t^2-1}} T_{2k+1}\left(\frac{1}{t}\right) dt \qquad (7.36)$$

The integral in the summation can be reduced to the integral $G_{2k+1}(u)$ where

$$G_n(u) = \int_0^{\pi/2} \sin(u \sec\theta) \cos n\theta \, d\theta \qquad (7.37)$$

This integral apparently cannot be readily expressed in closed form using simple known functions. Since $B(\eta) = (\eta/b)^{-1/2} F(\eta/b)$,

$$F(\lambda) = \lambda^{\frac{1}{2}} B(b\lambda) \qquad (7.38)$$

and so from (5.28),

$$\phi^+ = H_0 \int_0^{\infty} \lambda^{\frac{1}{2}} B(b\lambda) \sin\lambda z \, e^{-\lambda x} \frac{d\lambda}{\lambda} - (1+R) H_0 z$$

$$(7.39)$$

$$\phi^- = -H_0 \int_0^{\infty} \lambda^{\frac{1}{2}} B(b\lambda) \sin\lambda z \, e^{\lambda x} \frac{d\lambda}{\lambda} - T H_0 z$$

This is the required solution.

Another matrix equation for the a_i's can be found by multiplying (7.22) by $T_{2n+1}(s)$ and integrating from -1 to 1. The identity

$$t^2 \sum_{k=0}^{\infty} a_k T_{2k+1}(t) = \sum_{k=0}^{\infty} \left(\frac{a_{k-1} + 2a_k + a_{k+1}}{4} \right) T_{2k+1}(t) \tag{7.40}$$

is required where $a_{-1} \equiv a_0$. The integral

$$f(k,n) = \int_{-1}^{1} T_{2k+1}(t)\, T_{2n+1}(t)\, dt =$$

$$= \frac{1}{1 - 4(k-n)^2} + \frac{1}{1 - 4(k+n+1)^2} \tag{7.41}$$

is also necessary. This gives the infinite set of equations in an infinite number of unknowns

$$-\pi \sum_{k=0}^{\infty} \frac{a_k f(k,n)}{2k+1} + \frac{2\pi Z_s}{i k Z_0 b} \frac{\pi}{2} \left\{ \frac{a_{n+1} + 2a_n + a_{n-1}}{4} \right\} =$$

$$= b^{3/2} \sqrt{\frac{2}{\pi}} \left(\frac{1 + R - T}{2} \right) \sum_{k=0}^{\infty} C_k f(k,n) \tag{7.42}$$

$$n = 0, 1, 2, \cdots, \infty$$

This probably would be easier to adapt for computer solution than would (7.33).

(b) Solution of (7.12) by Legendre Series

The orthogonality properties of Legendre polynomials are used here to find the solution in terms of a Legendre polynomial expansion. It has been found by Casey (1979) that

$$I_{m,n} = \int_{-1}^{1}\int_{-1}^{1} P_{2n-1}(t)\, P_{2m-1}(\tau) \ln|t-\tau|\, dt\, d\tau =$$

$$= \frac{2}{(m+n)(m+n-1)\left[4(m-n)^2-1\right]} \qquad (7.43)$$

This will be used to solve equation (7.12). Expression (7.18) has already been given for the right-hand side of (7.12). The unknown h(t) can be expanded in Legendre polynomials. Let

$$h(t) = \sum_{n=1}^{\infty} b_n P_{2n-1}(t) \qquad (7.44)$$

In order to use orthogonality, $t^2 h(t)$ must be expressed as a series of Legendre polynomials. Identity 8.915 5., page 1026 of Gradshteyn and Ryzhik (1965) can be used to do this. One finds that

$$t^2 P_{2n-1}(t) = \sum_{p=0}^{2} a_p(n) P_{2(n-p)+1} \qquad (7.45)$$

$$n = 1, 2, \cdots, \infty$$

$$a_0(k) = \frac{(2k+1)(2k)}{(4k+1)(4k-1)} \qquad (7.46a)$$

$$a_1(k) = \frac{1}{3}\left\{ 1 + 2\, \frac{2k(2k-1)}{(4k-3)(4k+1)} \right\} \qquad (7.46b)$$

$$a_2(k) = \frac{(2k-1)(2k-2)}{(4k-1)(4k-3)} \qquad (7.46c)$$

Note that $a_2(1) = 0$. Substituting (7.18), (7.44) and (7.45) in (7.12), one arrives at

$$\sum_{n=1}^{\infty} b_n \int_{-1}^{1} P_{2n-1}(v) \ln|s-v|\,dv \; +$$

$$+ \frac{2\pi Z_s}{ikZ_0 b} \sum_{n=1}^{\infty} b_n \sum_{p=0}^{2} a_p(n) P_{2(n-p)+1}(s) =$$

$$= b^{3/2}\sqrt{\frac{2}{\pi}}\left(\frac{1+R-T}{2}\right) \sum_{n=1}^{\infty} d_n P_{2n-1}(s) \qquad (7.47)$$

Multiplying through by $P_{2m-1}(s)$, integrating from -1 to 1, and simplifying, one obtains

$$\left(\frac{4m-1}{2}\right) \sum_{n=1}^{\infty} I_{m,n} b_n + \frac{2\pi Z_s}{ikZ_0 b} \sum_{p=0}^{2} a_p(m+p-1) b_{m+p-1} =$$

$$= b^{3/2}\sqrt{\frac{2}{\pi}}\left(\frac{1+R-T}{2}\right) d_m \qquad (7.48)$$

$$m = 1, 2, \cdots, \infty$$

This is an infinite set of equations in an infinite number of unknowns and can be solved approximately on the computer. Once the b_m's are found, the solution can readily be obtained. Recall that $g(t) = (1/t^2)h(1/t)$. This makes

$$g(t) = \frac{1}{t^2} \sum_{n=1}^{\infty} b_n P_{2n-1}\left(\frac{1}{t}\right) \qquad (7.49)$$

Substituting this in (7.5), one obtains

$$B(u) = \sqrt{\frac{2}{\pi}}\left(\frac{1+R-T}{2}\right) b^{3/2}\, J_{\frac{3}{2}}(u) \; +$$

$$+\sqrt{\frac{2}{\pi}}\sqrt{u}\sum_{n=1}^{\infty} b_n \int_1^{\infty} t^{-2} \sin ut \; P_{2n-1}\left(\frac{1}{t}\right) dt \qquad (7.50)$$

This last integral can be reduced to $H_{2n-1}(u)$ where

$$H_k(u) = \int_0^{\frac{\pi}{2}} \sin(u \sec\theta)\, P_k(\cos\theta) \sin\theta \, d\theta \qquad (7.51)$$

An obvious simplification of this integral could not be found. The expressions for the ϕ's are those in (7.39).

VIII. RECOMMENDATIONS

This report provides an analytic solution to the problem of penetration of a composite skin panel by a quasi-static magnetic field at normal incidence. The resultant H-field is given by equation (5.9)

$$\vec{H} = -\nabla\phi$$

where ϕ is given by (7.39). The $B(b\lambda)$ in these expressions is given by either (7.36) for Chebyshev polynomials, or (7.50) for Legendre polynomials. The coefficients a_k and b_n in each of these expressions must be found for every particular gap width 2b and sheet impedance Z_s by using either equations (7.33) or (7.42) for Chebyshev polynomials or (7.48) for Legendre polynomials. Once these coefficients have been found numerically, then theoretical expressions can be found for the H-field.

These theoretical expressions involve either the function $G_n(x)$ of (7.37) or the functions $H_k(x)$ of (7.51). This is unfortunate because neither of these functions can apparently be expressed in terms of simple special functions in a concise manner.

It is clear that several areas of this problem need to be explored further. First, the special case $Z_s=0$ in the general equations needs to be studied. Second, simple approximate results need to be found. Finally, numerical studies of the equations need to be done.

First, it is desirable to see how these equations simplify for the special case $Z_s=0$. Analytic solutions for this case have been obtained in section VI. The results of section VII need to be checked. By comparing the results of sections VI and VII, a simple check can be made. Also, careful study of this case may provide some insight into how to treat the case when Z_s is very small, but not zero. Study of this special case could provide some valuable mathematical identities which might be of use in the general problem.

Secondly, simple approximate results need to be found. The present form of the equations is extremely complicated. This is because no approximations have yet been made in the results. It is not clear how many terms must be kept in the Chebyshev or Legendre series. If, for example, only two or three terms are needed, then significant simplification of the results would occur. There may also be some way to come up with an approximate analytic solution to the infinite number of equations in an infinite number of unknowns problem. This would considerably simplify the solution process for particular Z_s's. Some way of evaluating the $G_n(x)$ and $H_n(x)$ functions of equations (7.37) and (7.51), respectively, needs to be found. An approximate method, such as stationary phase integration, might give satisfactory approximate results.

Finally, numerical studies of the equations need to be made. The equations need to be solved numerically for specific slit widths and Z_s values. Charts and graphs of the field patterns need to be prepared and conclusions about them need to be made. This would fulfill the last half of the objectives stated in section II. The general integral equations of section IV need to be solved numerically and compared with the solution obtained by the present method. By comparing the solution by these two different methods, confidence in the validity of the results could be attained.

Several possibilities for further research in related areas exist. Experimental measurements could be made of a simulated slit problem and the results compared with the analytic results. Calculations could be made for the other polarization of incident field on an impedance sheet with a contact resistance to simulate current flowing across a seam. Studies of all kinds of apertures in impedance sheets could be made. These are only a few of the many possibilities for further research into this area.

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FINAL REPORT

PART I. TECHNOLOGY ASSESSMENT ON THE CRITICAL AND STRATEGIC STATUS OF TANTALUM METAL

PART II. TECHNOLOGY ASSESSMENT CONCERNING THE CURRENT STATUS OF ALLOY AND COATING DEVELOPMENT PROGRAMS FOR REFRACTORY METAL SYSTEMS CONTAINING Cb, Mo, Ta, AND W

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Part I:

Technology Assessment
on the Critical and Strategic
Status of Tantalum Metal

ABSTRACT

Because of a deep concern about the limited supply of tantalum resources for the Aerospace industry, the possible formation of tantalum cartels and overt political activities by some tantalum-rich nations, this study on the tantalum situation was initiated and thereby justified. Although of short duration and limited scope, this study attempts to focus on the tantalum problems that face primarily the Aerospace industry of today and in the future. Specific recommendations are given with the intention that these suggestions might lead to some definite undertakings for meeting the projected needs for tantalum metal.

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INTRODUCTION

The combination of market cartels and political instabilities within certain nations have highlighted the fact that the price-supply relationship for any imported material can be strongly influenced by the unpredictable vagaries of world events and local politics. In recent months, much concern has been expressed with regard to one vital area of nonrenewable mineral resources; i.e., petroleum deposits. Yet, petroleum is not the only foreign-supplied commodity upon which the United States is highly dependent, see Figure 1. Here it is to be seen that the United States imports more than fifty per cent of all mineral supplies for needs which involve chromium, platinum, osmium ruthenium, iridium, tantalum, aluminum, cobalt, manganese, tin, nickel and columbium. More important is the fact that the United States is almost totally dependent on other nations for its supply of certain important aerospace minerals; viz., chromium, tantalum, aluminum, cobalt and manganese.

Because of a deep concern about the limited supply of tantalum resources for the Aerospace industry, the possible formation of tantalum cartels and overt political activities by some tantalum-rich nations, this study on the tantalum situation was initiated and thereby justified.

Historical Information[2]

Tantalum (Ta) is a metallic element in the fifth group of the periodic system, which includes the metal vanadium. It derives its name from the Greek mythological King Tantalus, because of its ability to 'absorb' acids. It is not very richly distributed in nature, but is found with columbium and many other rare minerals. It was first discovered in a curious way. In 1801 C. Hatchett found a new element in a mineral from Massachusetts, to which he gave the name 'columbium'. In the following year A.G. Ekberg found a new element in yttrium minerals from Sweden, and called it tantalum. Then followed the failure of an attempt to prove these two new elements identical. Other new elements discovered during later years confused the issue considerably, but eventually tantalum was established as a metal in its own right and is no longer confused with columbium (niobium).

In a pure form it was obtained by Berzelius in 1820 by the heating of potassium tantalofluoride with potassium. The pure metal was not obtained until 1905, when Werner von Bolton fused compressed metal of the type obtained by Berzelius in the electric furnace from which air was excluded.

Ore Deposits[2]

The principal sources of tantalite, the ore, are Nigeria, Zaire, Portugal, Rhodesia, Uganda, South Africa, South-west Africa, Australia, Mozambique, French Guinea, Brazil, Spain, Canada, Sweden and the United States. Of columbite, the principal sources are Nigeria, Rhodesia, Uganda, South-west Africa, Malaya, Australia, Zaire, Madagascar, Mozambique, Bolivia, French Guinea, Argentina, Brazil Portugal, Spain, Norway, Sweden and the United States. The production of columbite is forty times as great as that of tantalite. By far the largest importer is the United States.

Extraction Techniques[2]

In modern production, the ore tantalite $Fe(TaO_3)_2$ obtained from columbite $Fe(NbO_3)_2$, is comminuted to a powder and then fused with caustic soda, from which product the silica is eliminated by extraction with water. Other materials soluble in acid, such as manganese, are eliminated by means of hydrochloric acid, leaving the insoluble hydroxides of tantalum and niobium as residues. After dissolution in hot hydrofluoric acid in the presence of potassium ions, the solution is allowed to cool, after which tantalum double fluoride (K_2TaF_7) is crystallized out by repeated fractional crystallization, leaving behind niobium double fluoride (K_2NbOF_5) which is much more easily dissolved.

This process, however, is only suitable when tantalum is obtained from tantalite ore. If the ore contains a high niobium content, liquid-liquid extraction is employed instead, and this is the process most commonly used, because niobium is also required from the ore, and Nb is not as easy to recover.

There are, however, other means of obtaining the metal, such as the thermit process already mentioned, in which caustic soda and the double fluorides are used. Electrolysis is another method, using molten salts of the double fluoride. A mixture of the oxide and carbide can be thermit-reduced as follows:

$$Ta_2O_5 + 5TaC = 7Ta + 5CO$$

Important Characteristics[2]

Tantalum is a heavy metal with a steel-blue color, which, when the metal is polished, becomes platinum-white. It has a high melting point, and when exposed to the atmosphere forms a tough and impermeable oxide film serving to protect it from corrosion. In consequence, it is the most resistant of all the metals to acid attack. Ta withstands many chemicals, including organic acids, fatty acids, and, indeed any one acid other than hydrofluoric acid. Caustic alkalis attack Ta with difficulty only. It is thus superior even to platinum in resistance to corrosion, and being less expensive, can be substituted for Pt in many applications.

Ta is tough, ductile, malleable and capable of being readily welded. It has no effect on water even at temperatures up to 600 deg. C. (1112 deg. F.), but at this same temperature it will burn in oxygen. Its machinability is similar to that of cold-rolled steel, and either tungsten carbide or high-speed steel tools can be used. Carbon tetrachloride or light oil will serve as a cutting fluid, and machine oil is sometimes recommended as a lubricant. Ta automatically rectifies an alternating current, and is capable of being pressed, sintered, hammered or swaged. The impurities that are usually found in processed tantalum include and called it tantalum. Then followed the failure of an attempt to prove these two new elements identical. Other new elements discovered during later years confused the issue considerably, but eventually tantalum was established as a metal in its own right and is no longer confused with columbium (niobium).

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The metal is produced in powder form from tantalite. Only one process produces the metal in massive form as 'hairpins', but this is merely for experimental laboratory work. In the difficult recovery of the metal, the powder is obtained, washed to eliminate impurities, heated in a vacuum and by hydraulic pressure formed into bars, which are resistant in themselves to an electric current, so that the heat generated in the passage of such a current serves to sinter them. Bars can then be formed into sheet or wire, and because Ta bars do not readily work-harden, it is not often necessary to give intermediate annealings during powder forming processes. If such an annealing is required, however, it is carried out in a high vacuum.

The compactibility of tantalum is good. In general a small amount of extremely fine-ground titanium is added to the normal powder to make molding easier. The ingot sizes are, typically, 30-in. long by 2-1/2-in. wide by 1/4-in. thick, and weigh mostly from 8 to 12-lb. each. The pressure required for forming into bars without pre-sintering is about 50-tons/sq. in.

Important Applications[2]

Tantalum has a higher melting point than molybdenum and is much more ductile. When recrystallized, Ta is much more ductile than either molybdenum or tungsten. Its properties make Ta particularly suitable for grids in electronic power tubes, because it has high gas absorption and retention at lower pressure and temperatures than most other metals. In resistance to corrosion Ta is equal to glass, but has a much higher rate of heat transfer. Ta also has the special property of forming anodic oxide films which are self-healing.

When heated in nitrogen at 600 to 900 deg. C, Ta absorbs the gas to form nitrides, and this means that the metal becomes embrittled and may raise its hardness to 600 Brinell.

The production of tantalum has greatly increased in recent years. It is being extensively used for stills, agitators, containers, pipes, etc., in the chemical industry because of its strength, ductility, workability and corrosion resistance. Ta is also applied to equipment used in combination with plastics and ceramics, the principal uses being for heat exchangers, and for the absorption, evaporation and condensation of hydrochloric acid. Its oxide film stability makes Ta valuable for wet rectifiers. Ta is also applied to self-healing electrolytic condensers and lightning arresters. Centrifugal pumps are another application for Ta.

Tantalum is also used for capacitors because of the wide range of temperature over which Ta works effectively (-60 to 200 deg. C or -75 to 400 deg. F). Ta is valuable, too, in 'getters' and grids for electronic tubes, particularly in ultra-high-frequency transmission. Additional uses include steam turbine blades, valves, nozzles,diaphragms, spinnerets for the production of rayon, and the tips of fountain pen nibs. There are applications of tantalum also in the field of high vacuum. Tantalum anodes for electric power tubes are used, especially in service at ultra-high-frequency.

Surgical uses are numerous, including the use of cover wires for uniting fractured bones and implanted plates for replacing lost skull sections. Nerves and tendons have been sewn together with fine tantalum wire and protected by foil of the same metal. Dental instruments also make use of tantalum. Ta metal does not irritate living tissues, and this compatibility makes it most serviceable in surgery and medicine.

Ta is being studied at the present time as a possible alloy base for future thermospheric structures and 'hot' aerospace engine environs: e.g., directionally-solidified eutectic alloys in military applications. As an alloying element in the manufacturing of steel alloys, Ta has not gained widespread popularity. This situation exists because, for most applications, Ta is inferior to niobium in the important characteristic of specific gravity. Ta has, however, been added to austenitic stainless steels to form carbide, thereby preventing intergranular corrosion, and to nitriding steels as a means of speeding up the formation of the nitride case, but in both instances niobium is better. Ta has, however, been used on an increasing scale as a 'hard metal' for cutting and other tools, by reason of the extra toughness obtained when the tools contain Ta and/or tantalum carbide.

Because of its hardness, toughness and ductility Ta is used for the manufacture of linings of pipes and tanks for the transport and storage of dangerous fluids.

The metal is usually supplied as ferro-tantalum, in which form Ta is alloyed to steel, but Ta is also sold as sheet or wire, of 99.95 percent purity, at prices either per pound or per kilogram. An alloy of tantalum with tungsten has been successfully used for special springs working at high temperature and high vacuum. Use is made of tantalum in electronic tubes for radar, and potassium tantalum fluoride has a catalytic application in making synthetic rubber. At one time, tantalum was used for electric lamp filaments.

Limitations[2]

Tantalum is not resistant to corrosion in galvanic couple action. Excessive impurities in its composition lead to lower elongation percent, and high yield and tensile strengths, but has little effect on corrosion resistance. If the metal is to be used as an alloy, from 7.5 to 10.0 percent tungsten should be added to give superior yield and tensile strengths combined with a higher temperature of recrystallization. If electronic properties are primarily required, thorium should be added.

In melting the metal, oxygen, hydrogen, nitrogen and carbon should be carefully excluded, and melting should be done in a vacuum. If this is not possible, an inert gaseous atmosphere should be used. Annealing can be done at above 1050 deg. C (1920 deg. F), in high vacuum. The maximum reduction between annealing operations is more than 95 per cent. All the normal forming processes can be employed. The compacting pressure ranges from 10 to 60 tons/sq. in., being governed by the physical characteristics of the powder. Sintering should be done within the range 2300 to 2600 deg. C (4175 to 4700 deg. F) in high vacuum, which will eliminate harmful contaminants. The normal finishes of the metal are dull or bright for rolled sheet, and smooth dull for wire. Brazing with copper can be carried out in vacuum. Welding by the customary processes is possible, but it is essential to exclude air by use of inert techniques for tungsten arc, electron beam, resistance spot, or other suitable processes of welding.

DISCUSSION OF RESULTS

Recently, many important publications have been given to the concept that the world's resources shall not last indefinitely.[3-56] These articles of the open literature have been excellent surveys about the general condition that exists but none have been dedicated solely to the problem of tantalum metal and very few are concerned with the needs and priorities of the Aerospace industry. This study, although of short duration and limited scope, attempts to focus on the tantalum problems that face primarily the Aerospace industry of today and in the future. The intent of this study is to form certain specific recommendations that might lead to some definite undertakings to meet the projected need for tantalum metal.

The Problem of Reserves

Before any metal may be considered strategic or critical for the needs and priorities of the Aerospace industry, some clear definition is always required. Typically, the known U.S. reserves are taken to be the primary indicator for any such classification.(1) For the purposes of classification, reserves are defined as known and identified deposits from which minerals can be extracted profitably with existing technology and under current economic conditions.

Table I summarizes the present status for the U.S. reserves of aerospace mineral deposits, listing them as being either "abundant" or "scarce". Mineral reserves are taken to be "abundant" if the U.S. currently imports less than 50 percent of our Nation's needs and can maintain that position to the year 2000. Metals used in amounts that are at least 1 percent of the total projected aerospace requirements in the year 2000 are arbitrarily considered of "major" importance while metals making up less than 1 percent of the metals used in aerospace are considered of "minor" importance. Of the seven metals that are listed as of "major" importance to the Aerospace industry, it should be noted that current U.S. reserves for three of these metals are considered "scarce" (Al,Cr, and Ni).

One problem with such a classification is that surveys of this type consider the needs and priorities of *all* aerospace applications. If military engines are to be evaluated and classified separately, then the problem of U.S. reserves becomes a much greater issue. This is to say that military engines run hotter than commercial engines and that military engines are designed to more rigid requirements, especially with regard to tantalum, cobalt, columbium and manganese contents thereof. Accordingly, the problem of tantalum reserves is a problem of immense importance to the defense of our Nation. If this be true, what else can be stated about the problem of tantalum reserves?

The problem of tantalum reserves reaches new proportions of relevancy if one considers the fact that, at a time when this Nation's tantalum needs are greatest, almost nothing is being done to solve these urgent problems of demand and supply - Note Table II for a summary of the tantalum situation. From the data of Table II, it can be shown that, in recent years, imported tantalum ores are stable, exports of tantalum ore are increasing, consumption of tantalum is steady, the government stockpiles are depleting and industrial stockpiles have not changed in like manner - see Figure 2.

Prices for tantalum products continue to reflect a growing concern over the possibility of future shortages - in 1978, prices increased by about 30% for tantalum concentrates and by nearly 50% for tantalum metal as compared to the prices of 1977! Domestic demand for tantalum products is expected to exhibit a minimum increase of about 40% per year through 1985 and the supply needs for such demand can now come only from foreign production and industrial stocks. Although the United States has about 3.4 million pounds of identified tantalum ore deposits, no attempt is being made to utilize these resources - these ore deposits are classified (by industry) as being uneconomical based on 1978 price levels. As in the case for petroleum, it would seem that it is more expeditious for industry to exploit imported tantalum than it is to explore new tantalum recovery processes. New domestic tantalum deposits must be sought and new, or improved, methods for extracting tantalum from sub-marginal mineral materials and low-grade tin slags must be developed so that future requirements can be satisfied more economically to reduce our net reliance on imports - see Figure 3 for a summary of this critical import reliance.

According to information from the Bureau of Mines[57], tantalum metal is currently being utilized primarily by the electronics and chemical processing industries - note Figure 4. Of the amounts used in 1978, less than 2% were given to aerospace applications. Although the aerospace needs for tantalum may be great, it cannot be assumed that military applications of tantalum metal are any real threat to the scarcity of tantalum. The chief culprits for this problem of tantalum reserves involve those industries which require more tantalum... electronics and chemical processing. These firms continue to utilize tantalum in great quantities even though it is common knowledge that...

- Columbium *can be substituted for tantalum* in high-strength steels and superalloys.
- Aluminum *can be substituted for tantalum* in electronic capacitors.
- Silicon, germanium and selenium *can be substituted for tantalum* in electrical rectifiers.
- Glass, titanium, zirconium, columbium and platinum *can be substituted for tantalum* in corrosion-resistant equipment.
- Tungsten, rhenium, molybdenum, iridium, hafnium and columbium *can be stubstituted for tantalum* in high-temperature applications.

Although these substitutions are known to be economically feasible and attractive to the National needs or priorities, there is no apparent mechanism to force tantalum substitutions. The obvious thought is this... if excessive tantalum consumption is allowed to continue in such wild and uncontrolled fashion... how will we someday substitute for the dead engines of our imperiled military aircraft?

This problem of reserves and its relevance to the Aerospace industry is not a problem of numerical magnitudes. If numerical magnitudes alone are argued, the military needs of the future will always be badly considered. For example, Stephens *et al*[1] have shown that, by the year 2000, Aerospace industries will require only about 1.3% of the total U.S. demand for *all* the aerospace metals. More important, Stephens has shown that, by the year 2000, this Country will no longer have the capability to meet the total U.S. requirements for *any* aerospace element other than molybdenum - see Figure 5. It is clear that something needs to be done... and it must be done *now*!

The Producer Problem

According to References 3 and 57-61, domestic production of tantalum products (metal, alloys and compounds) is a producer problem of essentially four sources; imported concentrates, imported tin slags, tantalum-rich scrap and industrial stocks - see figure 6. This very typical source distribution is, by itself, not a producer problem... the producer problem that exists is simply this... in 1978, six companies with seven plants processed imported concentrates and tin slags to account for 100% of the 1978 production totals[60]. This apparently innocuous statement is graphically displayed by Figure 7. Here it is to be seen that, in 1978, domestic producers apparently met all market demands without using any tantalum scrap or stocks. This is to say that all production needs were ostensibly satisfied through the selective use of imports. In this way, producers have conserved their scrap and stockpiles through the use of *stockpile substitutes* called **imports**. Again it would seem that it is more expeditious for industry to exploit imports that it is to explore new tantalum recovery processes.

The producer problem is even more insidious if the variable of tantalum ore usage is evaluated in some detail. Figure 8 represents the current situation on how tantalum ores *are* processed.... inputs to the system of tantalum production include ore shipments from stockpiles and foreign ore imports while outputs to the system of tantalum production include ore consumption and the export of tantalum ores. What we need so desperately (quantities of tantalum ores) is bought from foreign nations and resold to other foreign nations! There are no apparent mechanisms to restrain these windfall profits by tantalum producers even when such profits are against the National needs, priorities and long-range interests.

If tantalum ore exports were somehow regulated, the efficiency of tantalum ore consumptions would be greatly enhanced. Figure 9 shows how efficiencies might increase if tantalum ore exports were not permitted... the process of tantalum usage, which is now out of control, could be brought into control. This is one method by which the producer problem can be greatly alleviated - see Figure 10 on how tantalum ores *should* be processed.

Earlier it was reported by Stephens, *et al*[1] who projected that, by the year 2000, Aerospace industries will require only about 1.3% of the total U.S. demand for all Aerospace metals and that, by the year 2000, this Nation will no longer have the wherewithal to meet the total U.S. requirement for *any* aerospace metal, except molybdenum. Figure 11 reveals the Bureau of Mines predictive data for the future needs of tantalum products according to their end use. Of interest here is the obvious question that, at these demand rates, how long can the producers survive... or, in other terms, how long will the world supply of tantalum continue to exist?

According to recent estimates by the Tantalum Producers Study Center (Brussels)[62], the average supply which existed at the 1977 level will continue for only twelve more years at the current rate of utilization. Note Table III... 1989 represents the terminal point for the existing world's supply of tantalum ore. New domestic tantalum deposits must be sought and new or improved methods for extracting tantalum from the now "uneconomic" mineral materials and low-grade tin slags must be developed... something needs to be done and it needs to be done *now!* Figure 12 represents one solution to the problem of tantalum production. If research and development investment monies are spent in massive amounts and in timely fashion, the threat of 1989 might be effectively managed. Through diligent development of new sources and new techniques, the World might be assured of a continuing supply of tantalum metal adequate to meet World demand at projected levels for many years to come. If, on the other hand, this problem is approached through the mechanism of typical R&D long-term management investment trends (Note Figure 12), it is quite likely that some scientist may someday find an appropriate solution for an inappropriate problem; e.g., what good could be served by new tantalum extraction techniques if tantalum sources were, at that time, non-existant? Clearly, the needs of today need to be served today, *not* tomorrow!

The Availability Problem

It has been shown that the U.S. has limited reserves of both "major" and "minor" aerospace metals [1]. In addition, because of either limited resources or lack of technological developments or favorable metal prices, domestic resources are not being mined. Because of these conditions the U.S. must turn to foreign sources to meet the aerospace needs as well as total U.S. metal requirements. Figure 1 illustrates the current percentage of various aerospace metals that are being imported and the major countries from which we obtain the metals. Figure 5 indicated that of the seven "major" aerospace metals, the U.S. in the year 2000 would not be able to produce any Cr and only 8 percent of the required Ni and 10 percent of the required Al. Figure 1 shows that the U.S. is currently importing 100 percent of its required Cr ore, 96 percent of the required Al ore, and 74 percent of the required Ni ore. Also, imports of the Pt group metals and of Co, Ta, and Mn are all in excess of 90 percent. In the case of Sn, approximately 80 percent is imported. The remaining Sn supply currently comes primarily from scrap and from selling of stockpiled Sn. The U.S. imports about 65 percent of the required supply of Cb. The remaining metals fall into the "abundant" category

(Table I), and imports range from approximately 40 percent for W to about 10 percent for Mg. Of the nineteen metals considered important to aerospace, it should be noted in Figure 5 that Mo is the only metal in which the U.S. maintains a net export position.

There are certain indirect factors which also affect the availability of important aerospace materials. For example, several existing or potential cartels are being considered by the countries that supply the Nation's minerals. The nature and content of recent news releases suggest that 'closed-door' meetings between mineral-producing countries may soon cause mineral-producer cartels to exist in the world market for aluminum, copper, chromium, platinum, tantalum and cobalt. Ostensibly, the 'official' purpose for these 'closed-door' meetings was to discuss mechanisms by which higher prices might be achieved for these important aerospace minerals on the World market. Although political differences and geographical separation make it more difficult for the mineral-exporting countries to form cartels similar to that formed by the oil-exporting Arab countries, several elements seem ripe for stronger control through cartels. Of particular concern is the potential cartel for Cr involving the countries of Rhodesia and the Republic of South Africa. Another possibility is that cartel which has been proposed to exist between Zaire and Nigeria for tantalum. In the latter case, collective cartel bargaining has been virtually suspended by the Civil War that now rages in Zaire. The combinations of market cartels, political unrest and even civil war pose great threats to the World price-supply relationships for all aerospace metals and, especially, for tantalum.

Another indirect factor that influences the use of domestic reserves is the effect that processing ores has on the environment. For example, the Cu industry has failed to start building new smelters to keep up with mining production because of new environmental restrictions being placed on the smelting operation. As a result, a potential Cu shortage can develop similar to the current oil shortage largely due to lack of required refining capacity. Insofar as tantalum is concerned, there has been no domestic mining-extraction industry since 1959 but this may have been caused by choice, not chance... it appears more expeditious for tantalum companies to exploit imports than to explore new extractive methods.

A third indirect factor that contributes to the problem of tantalum availability is the role that is played by ore allocations.... if tantalum ore imports were not resold to other producing nations, this Country could operate its tantalum resources at peak efficiencies (Refer to Figs. 8-10). In this way, tantalum shortages may develop similar to the problem of gasoline allocation difficulties that stem from supplying two-dollar-per-gallon markets (Europe) instead of supplying 95-cents-per-gallon markets (domestic).

The final factors that contribute to the problem of tantalum availability are the interactive roles exerted by apathy and/or a total lack of traceability. In the case of the former, no explanation is really necessary - it should suffice to say that *too many people care too little* about the tantalum situation and the threat that it represents. With respect to the latter, however, some discussion is, indeed, required. Although tantalum consumption can be monitored, tantalum production cannot be evaluated [57]. In 1978, two key suppliers of tantalum metal (Fansteel Metals and Kawecki Berylco) refused to divulge any figures on the amounts of tantalum that they produced... this they were able to do under the cover of "confidential proprietary information"[60]. It is now a truism that, where tantalum availability is concerned, we must be *more* concerned. The tantalum-rich scrap of military engine components that are retired-for-cause should represent an important source for badly-needed tantalum resources if good traceability did, in fact, exist. Here, traceability does not exist... some of this vital tantalum that once served important Air Force needs may be released to the tantalum producers so that it may one day become transistors in electronic toys... it is a pity that we are not *more* concerned. Since World War II, Japan has steadily invested tremendous sums of money into the purchase of mineral rights and ownership ... certain other nations (particularly the OPEC countries of the Middle East) have followed the example set by Japan. This trend of purchase power has continued without control or traceability to the point that important domestic mineral reserves are no longer controlled by the Nation in which the reserves occur! Conservative estimates predict that, by the year 1989, consortiums shall control what Congress cannot control. Concern about active traceability and real action is no longer enough... *more* concern and *more* action is now mandatory.

Methods to Improve The Situation

The inadequate status of our critical reserves and the finite character of our mineral resources and our dependence on other countries to supply the Nation with several strategic metals makes it imperative that efforts be increased to conserve the use of all such materials through immediate, positive-action programs.

One method to improve the tantalum situation is the business of more recycling activity by our Nation's primary metal producers. In recent years, producers have resisted recycling through the argument that tantalum scrap contains too much "old material" and not enough "new material" and, of course, "new " is more economical than "old"! Here, an explanation is in order; viz., "old material" is defined as scrap metal which has been exposed to a full service life in its own service environment (e.g., retired-for-cause jet turbine blades) while "new material" is scrap metal which has not seen any service applications (e.g., sections or cuttings from blooms or ingots during primary metal production and fabrication operations). In other words, the metal producer, if given a choice, will always choose to process scrap in terms of its purity... more pure is better than less pure. In this matter of recycling scrap metal, an important point exists and some explanation is necessary... the point of discussion is simply this: Are primary metals producers really recycling enough?

The current role of "old material" in the U.S. consumption arena is demonstrated by Figure 13[9]. This illustration reveals, for example, that about 12% of the U.S. needs for chromium metal are being met by the recycling of "old material" or "old scrap". Now it is to be understood that stainless steel scrap is the main source for reusable chromium and primarily as "new material" or new scrap". Isn't it ironic that any piece of stainless steel, "new" or "old", contains, as a minimum, 12 weight percent chromium metal? This bit of irony would suggest that producers are recycling "new" stainless steel but not "old" stainless steel... it is more economical to process "new" than "old". In fact, the truth of the matter is this... for every hundred pieces of scrap metal that contain chromium, less than 15 pieces are being reprocessed[1]. Unfortunately documented evidence reveals that, for the material which is available for recycling, only certain amounts are even reprocessed; e.g., copper - 61%, aluminum - 48%, nickel - 40%, titanium - 30%, iron - 26%, chromium - 15% and tantalum - 2%. Why does this situation exist... what needs to be done to improve the situation? In order to increase the use of strategic metals contained in "old material", new manufacturing technology must be developed, existing standards need revision and recycling requires stimulation.

It is easy for primary metal producers to process "new material" for this amounts to very little more than a remelting process. Such technology exists and has existed for many years since the time that metallurgists first learned to correct their mistakes in metal manufacturing. But, it is technically incorrect to say that 'reprocessing' is identical to 'recycling' and this was demonstrated by the previous example of stainless steel and the chromium problem. The truth is simply this.... manufacturing technology does not now exist for the recycling of all "old material". Industry needs to develop new extraction methods for the removal of all service contaminants from all "old material" (see Figure 14). It is imperative that new technology be supported so that economical recovery of strategically - vital metals may soon be a reality.

Before these new technologies for recovery of "old material" can ever become widely - accepted by consumers, it is also necessary that *this Nation must raise their Standards down.* For years now, the developing nations of the World have been amused by the restrictions of the American metal standards on composition, properties and structure. These nations are amused by the fact that all American standards (e.g., AISI, ASTM, ASM, ASME, SAE, SME, API, AMS and etc.) are based on one central theme... the use of virgin material by primary metal producers - a luxury which American metal manufacturers may one day be forced to classify as improper, wasteful or dangerous to our Nation's wealth! Perhaps, a true story will serve to demonstrate this point better.

The author of this report has a good friend in India who owns and operates a factory that uses only recycled stainless steel products. Each time this friend visits the U.S., he brings with him a different metallurgical sample from one of his many stainless steel products. These samples are brought to America to demonstrate a very important point... to this date, no American metallurgist has been able to look at his samples under a metallurgical microscope to correctly state the alloy type! I have played his game many times and I have always lost even though I am an expert on the microstructures of domestic stainless steels... but that's unimportant. The important thing is simply this... American metallurgists are taught and trained to think that *purity is better* and, as a result, our rigid Standards are given to the concept that good properties, structure and composition can exist only if purity prevails. And, if purity is to rule, then virgin material usage will also continue to be the preference of American primary metal producers. This is to say that, with the beginning of the Jet-Age, the aerospace metals Industry has concentrated practically all of their metallurgical design efforts toward the problem of getting higher concentrations of gamma prime (γ') so that higher strengths might exist at higher temperatures. This madness for more and more γ' is based on the simplistic view that *more γ' is better*! As a result of this totalitarian approach, we now have alloys and mixtures (e.g. directionally-solidified eutectics or rapidly-solidified powders) for which basic metallurgical parameters are either unknown or controversial... our meek acceptance of massive γ' concentrations and ultra-pure materials may have cost us more than that which we paid for higher hot strength. This ill-defined progress has left us with dwindling mineral reserves and metallurgists who worship the dual idols of purity and γ'. To this, my friend from India would say that American metallurgists will become good metallurgists only when they learn *to do it better more cheaply.*

As a necessary first-step toward this goal of doing it better more cheaply, American material standards need revision to reflect the changes that occur through the recycling of "old material" versus the recycling of "new material". For example, the "Cleanliness Charts" of ASTM should be accompanied by what can only be called "Dirtiness Charts". By the same token, the structure - property correlations of the AISI should be revised in terms of compositional variations caused by recycling "Grade I" versus "Grade II" scrap. If recycled stainless steel from India is inventable but unidentifiable, then American metallurgists need to invent more so that they may identify more. And, if our material *Standards are raised down* to permit more recycling, who knows exactly what may result... it could be that we would, at some point in the future, be better and more wiser with a greater endowment of regenerative resources for raw materials (and tantalum is no exception to this rule). In brief, research must be given to the development of new manufacturing technologies and revised materials Standards through recycling. A wider use of recycling may also be stimulated through adoption of favorable tax or regulatory policies by the appropriate Government agencies.

Another method to improve the tantalum situation would be to enhance the utilization of both substitutions and stockpiles. In previous discussion, it was pointed out that neither substitutions nor stockpiles are now being used to any appropriate extent... consumers resist any change called "substitution" and producers, if permitted, will always prefer to "hoard" their stockpiles. At this stage, it suffices to state only that there is no enforcement mechanism to ensure the use of either substitutes or stockpiles... this matter needs rectification. But, what can be said about the use of "substitution-stockpiles"?

Recent breakthroughs in an area called "Computer-Harmonics-Applications-Tailoring"(63) allows the development of what some choose to call "substitution-stockpiles". If all the attributes are known for a given materials application and if all materials selection criteria are properly integrated by an appropriate computer program... substitutes can be identified for further refinement and stockpiling. Although the techniques of computer harmonics are still in the infancy stage and, as yet, deal only with non-aerospace applications, the approach still merits consideration as a possible mechanism to improve the tantalum situation. Clearly, this area of computer harmonics will someday be an important tool that is best utilized by Integrated-Computer-Aided-Manufacturing (ICAM) design methods and processes.

In summary, the methods to improve the tantalum situation must include some immediate attention to these important facts and/or issues:

- The 3.4 million pounds of identified and "uneconomic" tantalum deposits in the United States need development.
- New tantalum recovery processes need to be established.
- Low-grade tin slags are a prime source of tantalum and these are not now being properly evaluated.
- Our net reliance on imports must be curbed through a better control of exported ore deposits.
- Tantalum utilizations by industry-at-large must be prioritized.
- Tantalum substitutes need to be enforced.
- The terminus point for the existing World's supply of tantalum ore (1989) must be circumvented.
- Cartels need to be countered by collective-embargos of the 'other kind' (food, clothing, medicine, technology and the necessities of all mankind).
- Environmental restrictions must be relaxed on matters of vital concern to the Nation's greatest needs, priorities and long-term interests.

- Allocation of tantalum ores by this Nation to other nations must be regulated.
- Apathy about the critical/strategic metals shortages must be eliminated through improved dissemination of reliable information at reputable information centers (Universities, not Air Force bases... in this way, the military bias will be disguised and, hopefully, ignored).
- Tantalum production must be a function that Government can monitor.
- Retirement-for-cause property of the U.S. Air Force should remain the property of the U.S. Government...tantalum of this type should not be used as tantalum for toys... such tantalum should be converted *by* the Government and *for* the Government.
- Are mineral resources within the U.S. being controlled by the consortiums of other nations?
- Do consortiums control what Congress cannot control?
- Recycling programs must be established.
- Greater recycling efforts need to be stimulated.
- New manufacturing technologies require development.
- Existing standards need revision.
- Oceanographic mining methods must be exploited.
- Is metallurgical purity the real solution?
- Is more gamma prime (γ') really better?
- Stockpiles must be monitored.
- Substitution-stockpiles need to be evaluated.

In brief, we need to attack this problem of the strategic/critical metal crisis so that *it may be done better more cheaply.*

CONCLUSION

Because of a deep concern about the limited supply of tantalum resources for the Aerospace industry, the possible formation of tantalum cartels and overt political activities by some tantalum-rich nations, this study on the tantalum situation was initiated and thereby justified. Although of short duration and limited scope, this study attempts to focus on the tantalum problems that face primarily the Aerospace industry of today and in the future. Specific recommendations are given with the intention that these suggestions might lead to some definite undertakings for meeting the projected needs for tantalum metal.

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APPENDIX

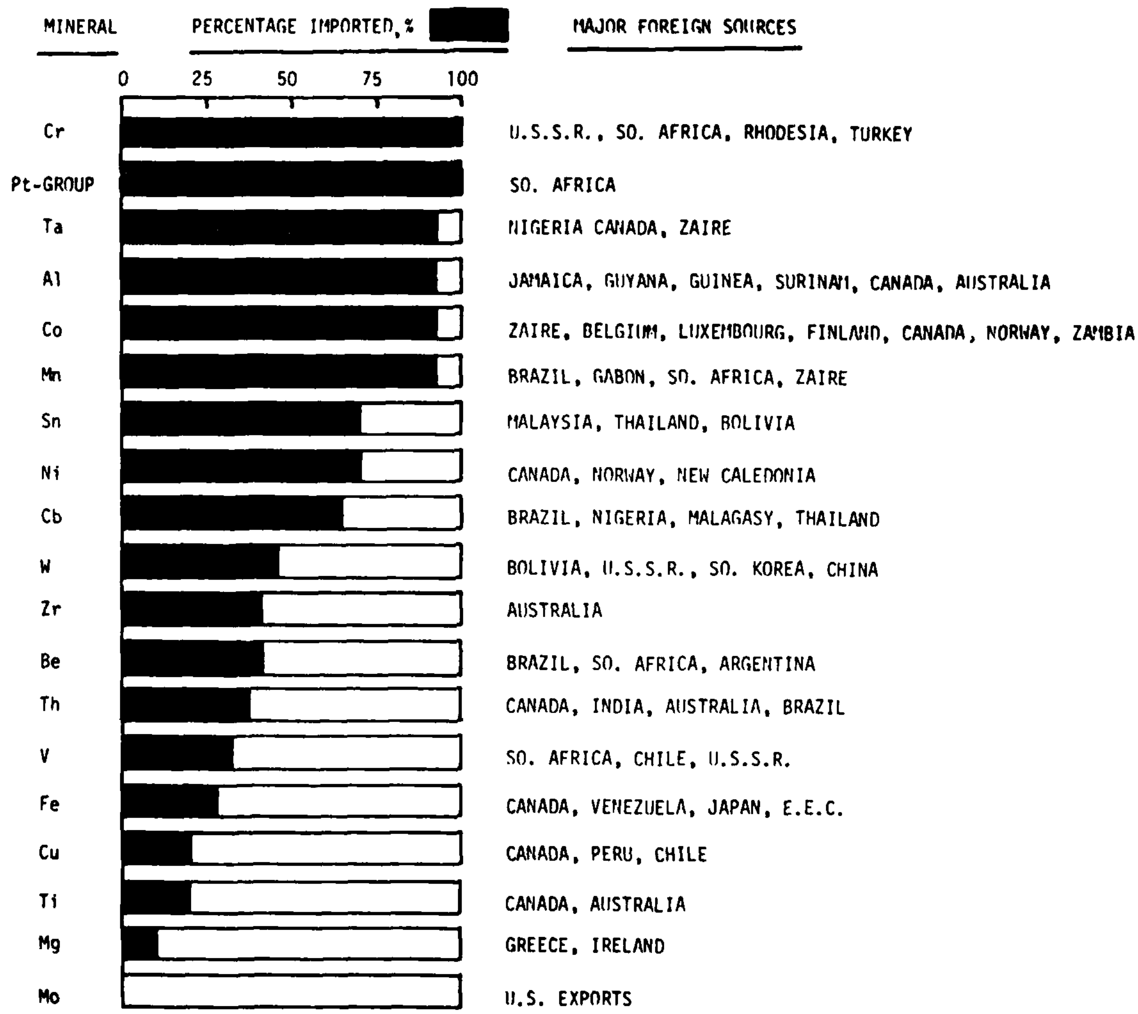


Figure 1. Sources of U.S. Mineral Supply and Percentage Imported. (Taken from Reference 1)

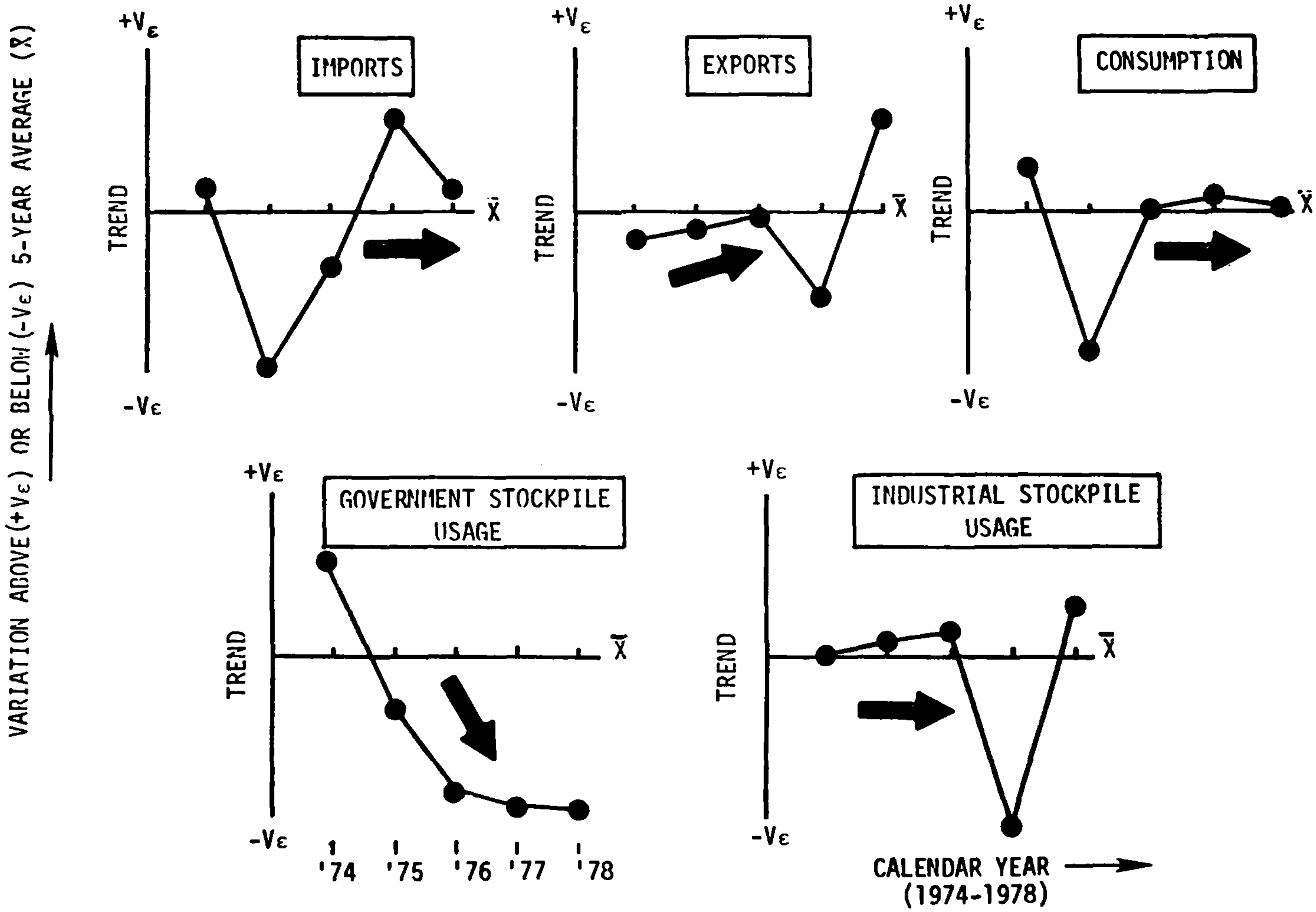


Figure 2. Market Variations for Tantalum Ores as a Function of Time.
(Data Taken from References 57 and 61).

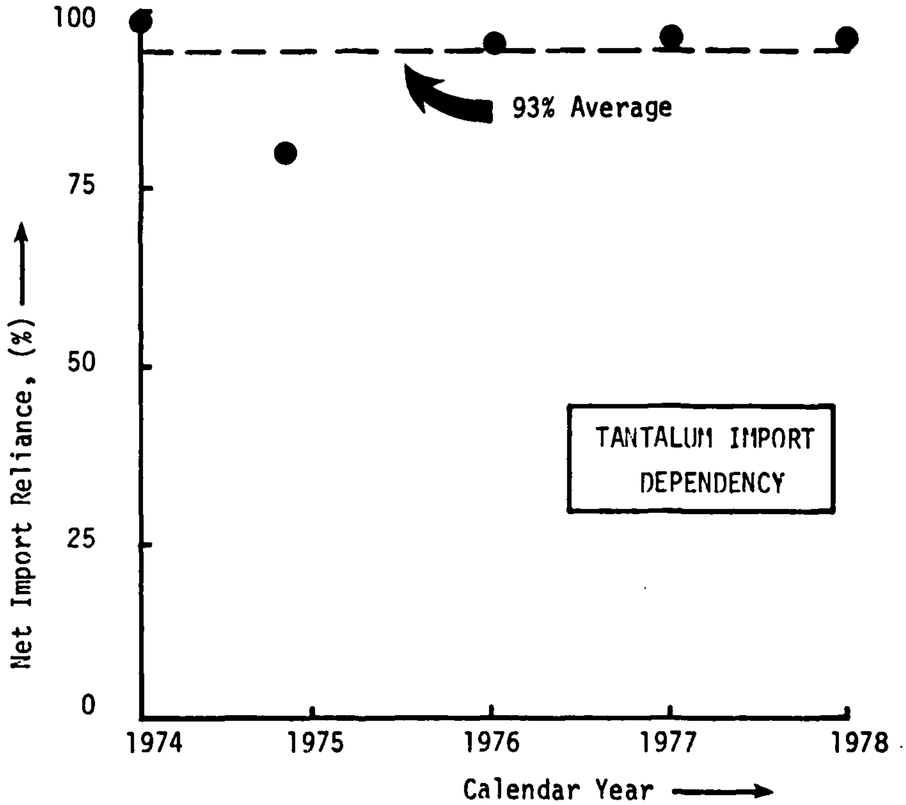


Figure 3. Net Import Reliance for Tantalum as a Function of Apparent Consumption (Taken from Reference 57).

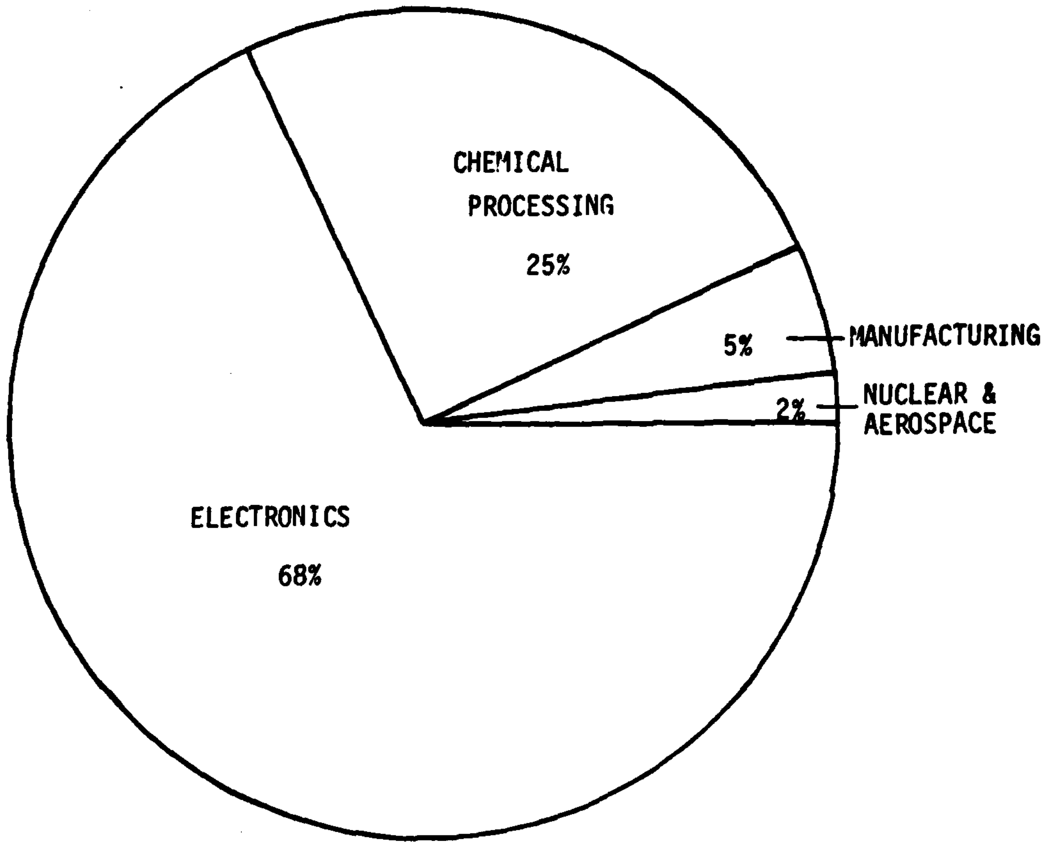


Figure 4. Composite Structure Chart for the 1978 Usage of Tantalum Metal (Data Taken from Reference 57).

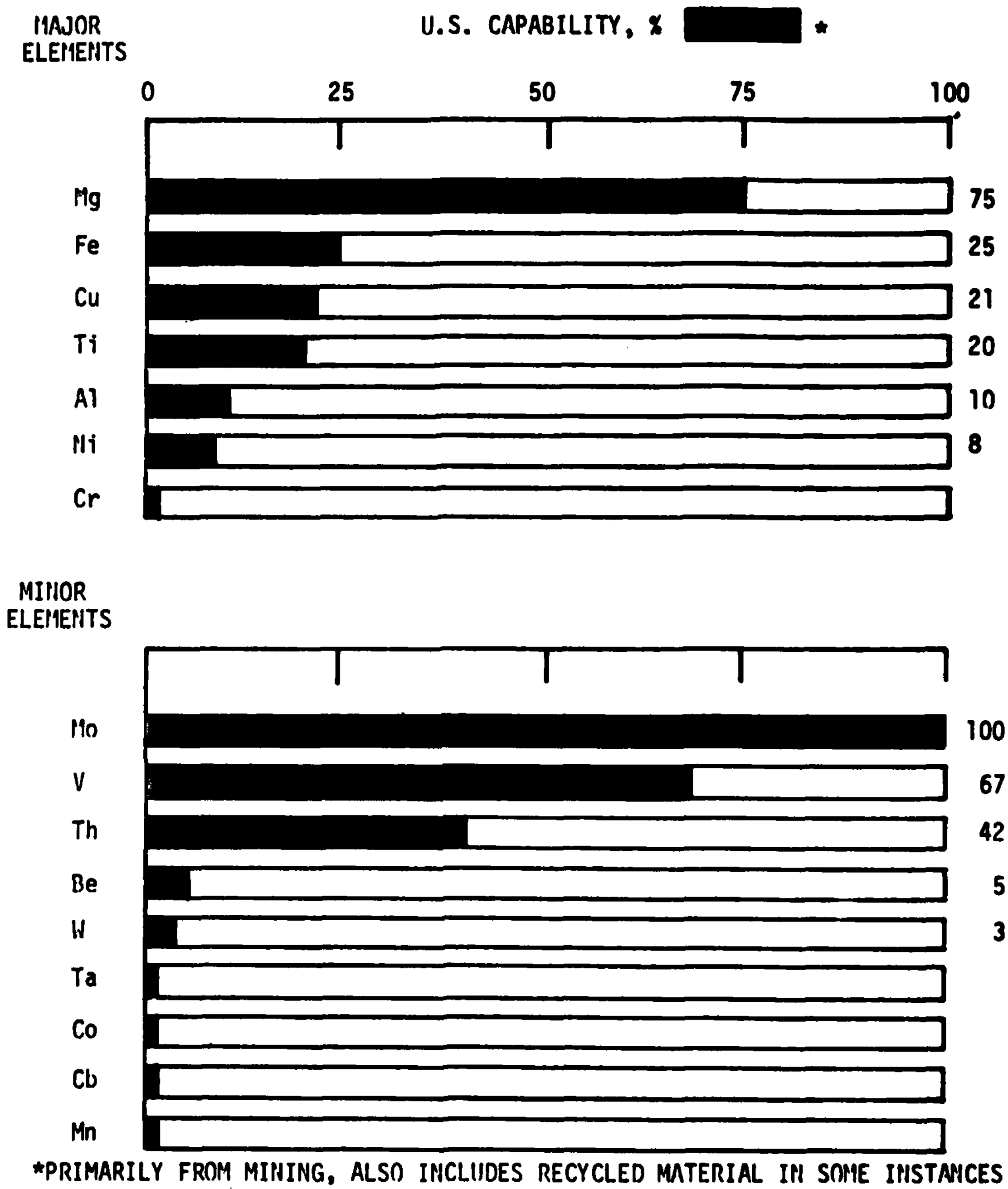


Figure 5. Capability of U.S. to meet total U.S. Requirements in Year 2000. (Taken from Reference 1).

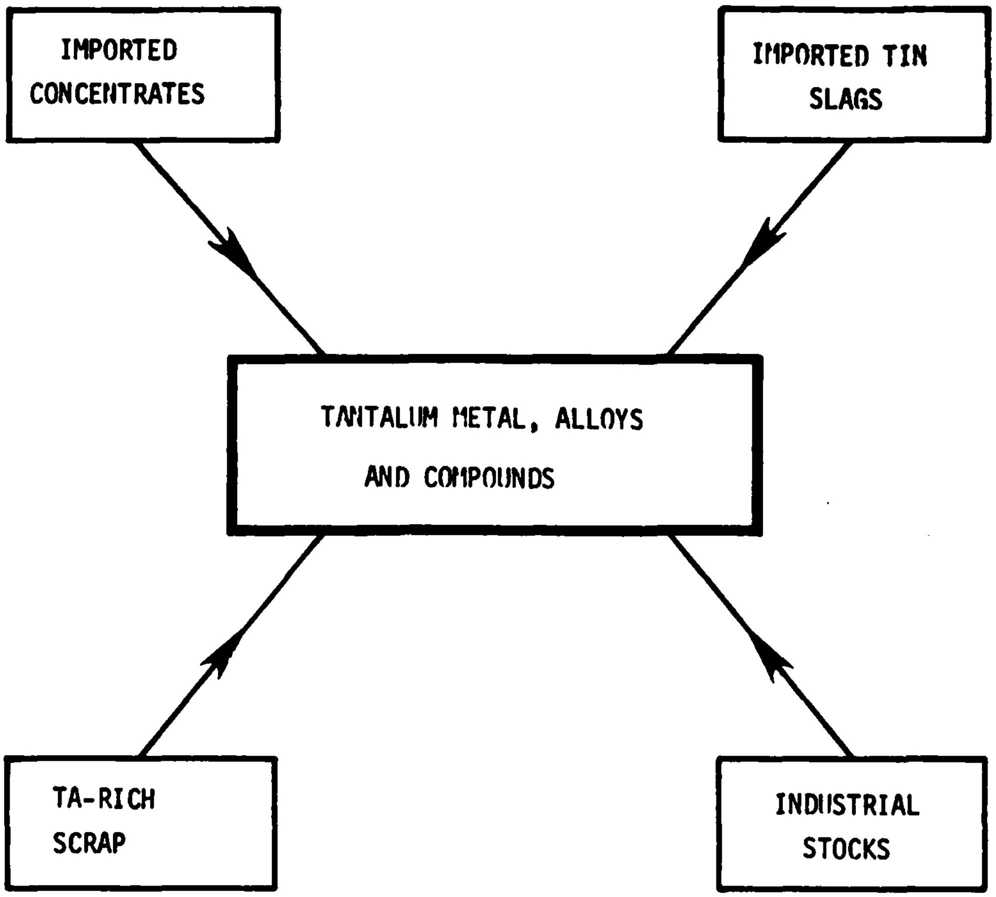


Figure 6. Sources of Domestic Production for Tantalum Products (Taken from References 3 and 57-61).

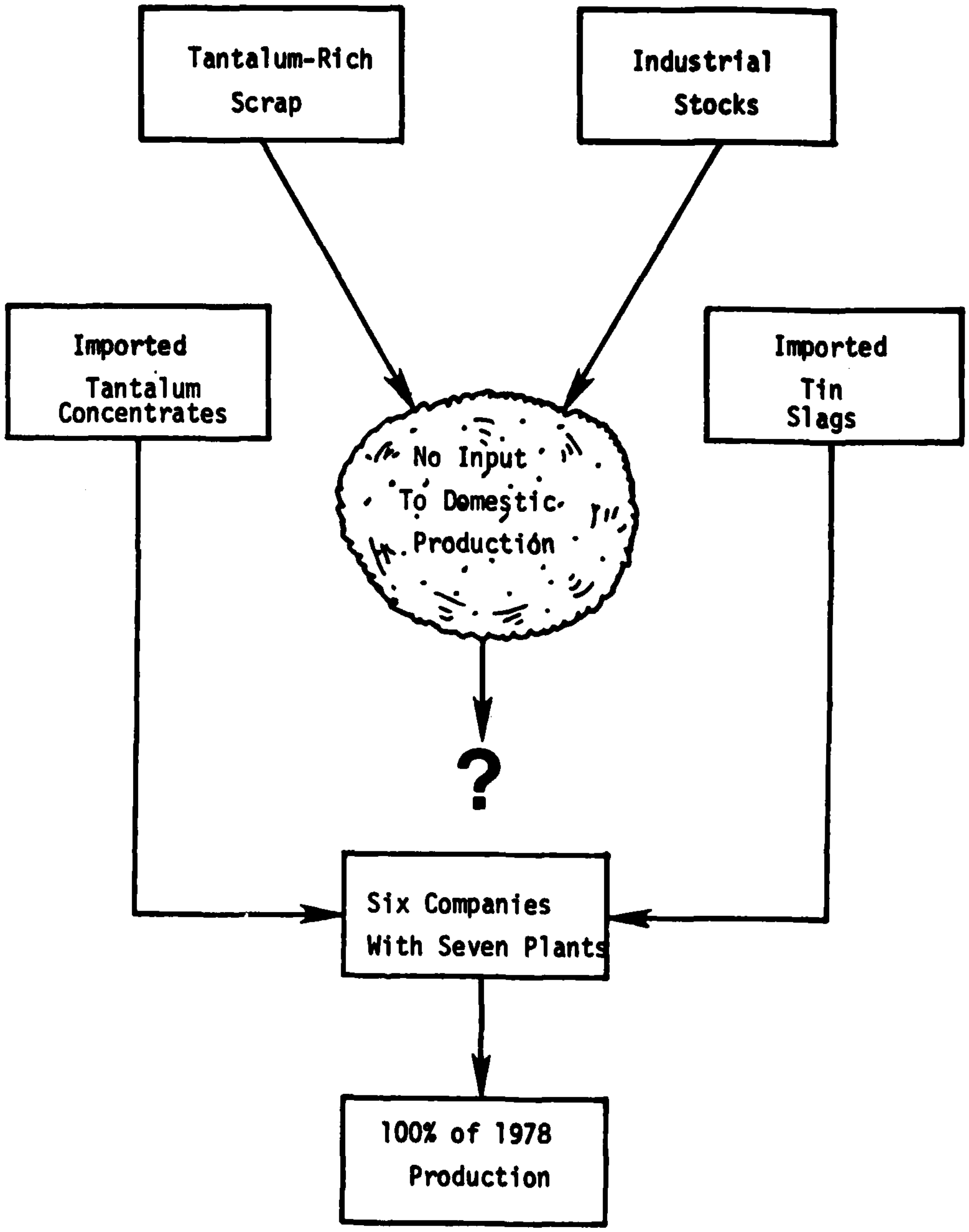


Figure 7. Allocation Problem in the Domestic Production of Tantalum Products (Taken from Reference 60).

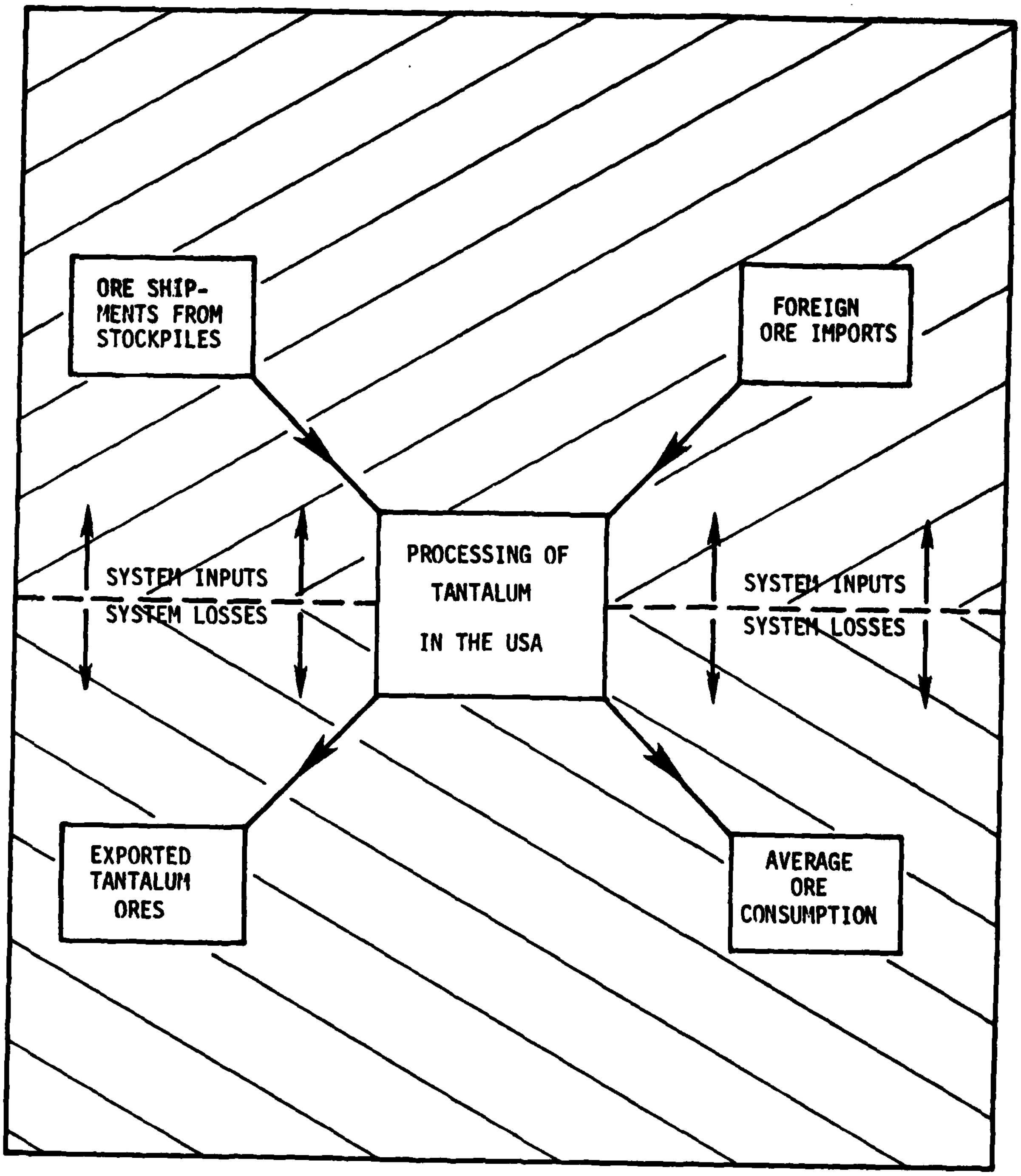


Figure 8. How Tantalum Ores are processed
(Data Taken from Reference 60).

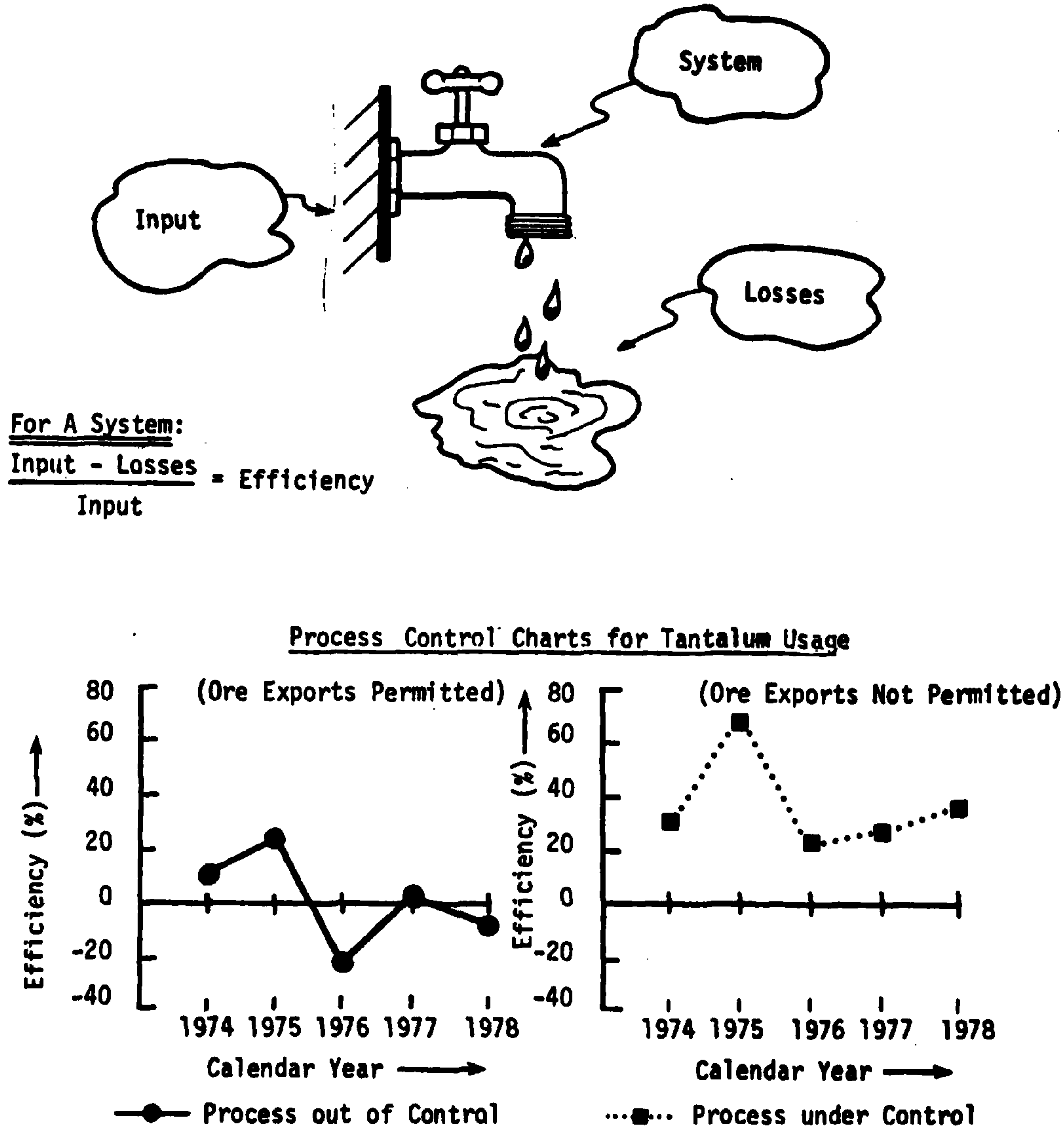


Figure 9. Efficiency Consideration for Tantalum Ore Consumption.

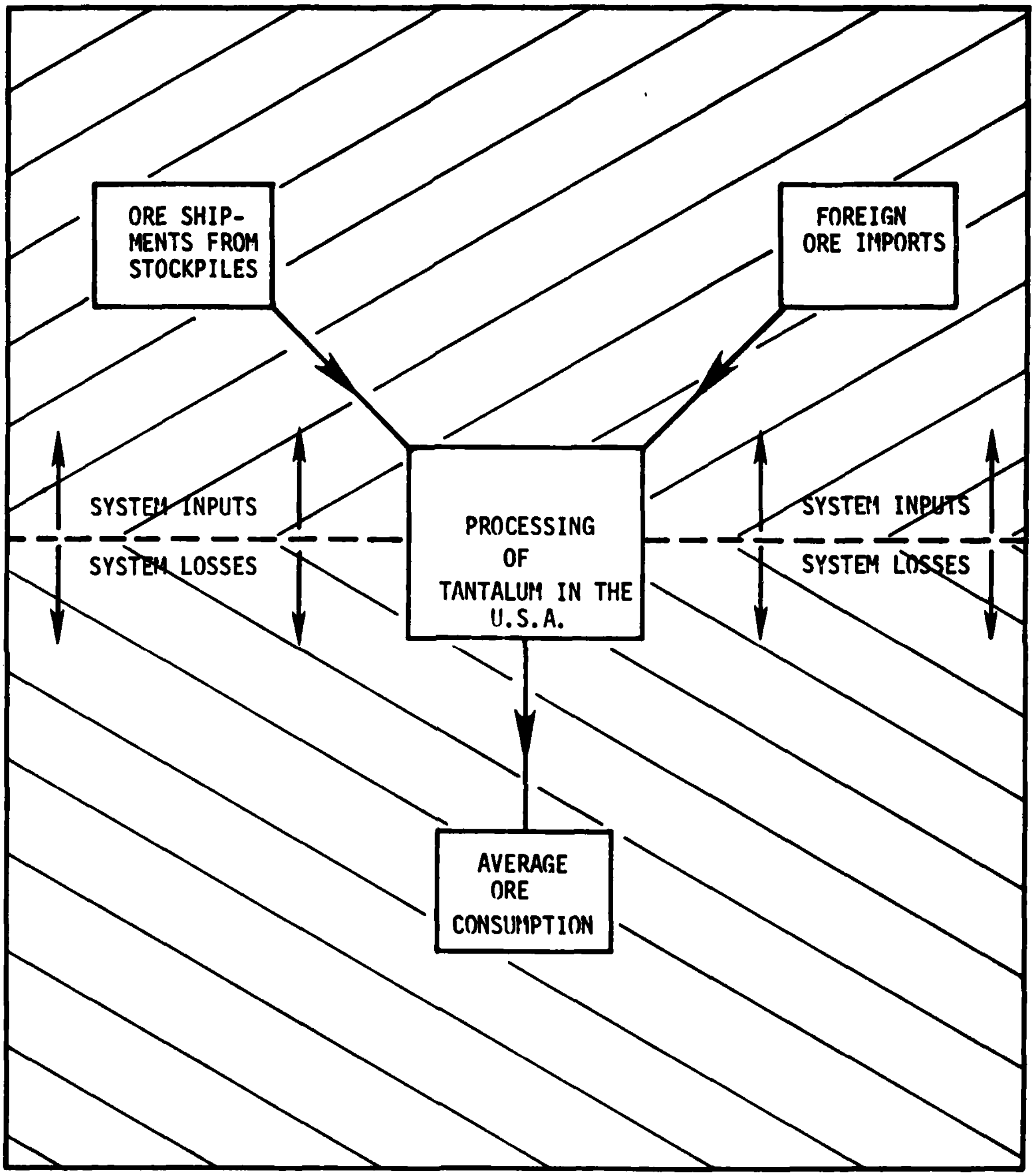


Figure 10. How Tantalum Ores *should* be processed (Compare to Figs. 8 and 9).

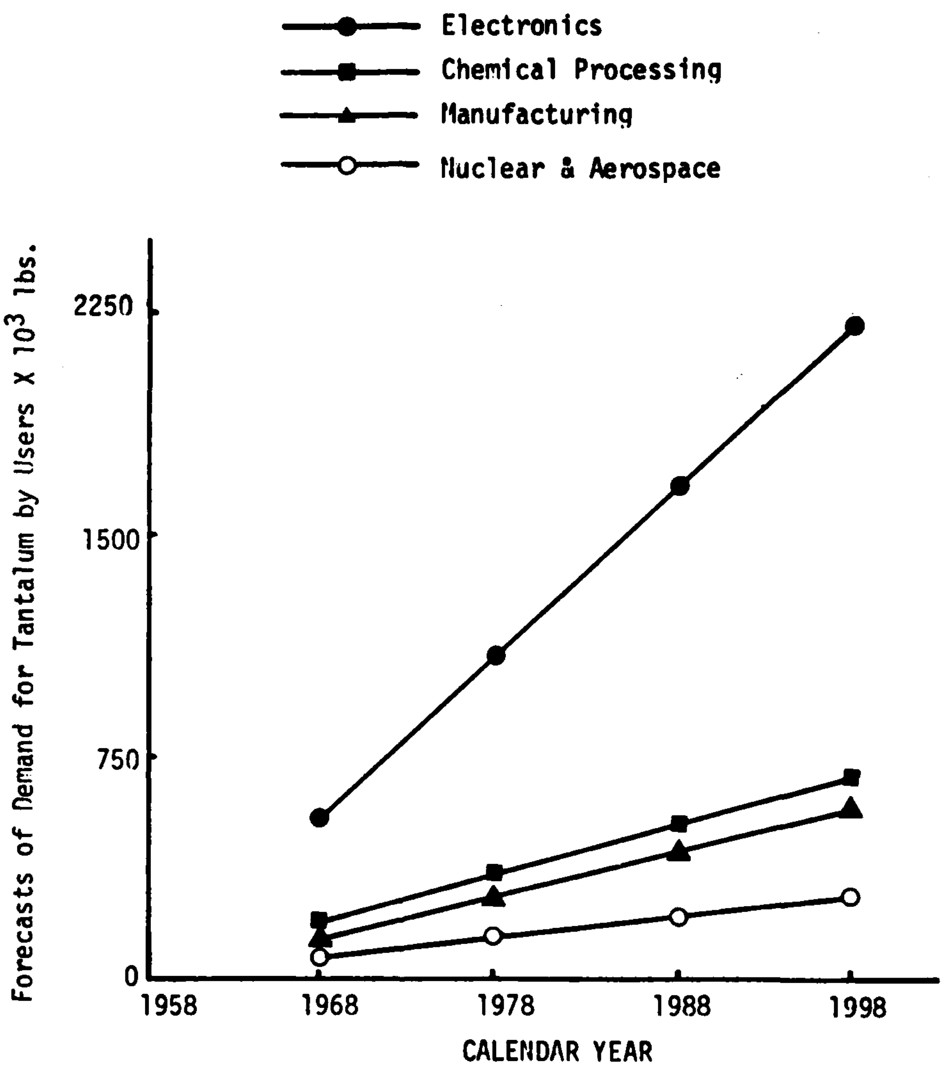


Figure 11. Future Needs for Tantalum Products (Data Taken from References 3 and 57).

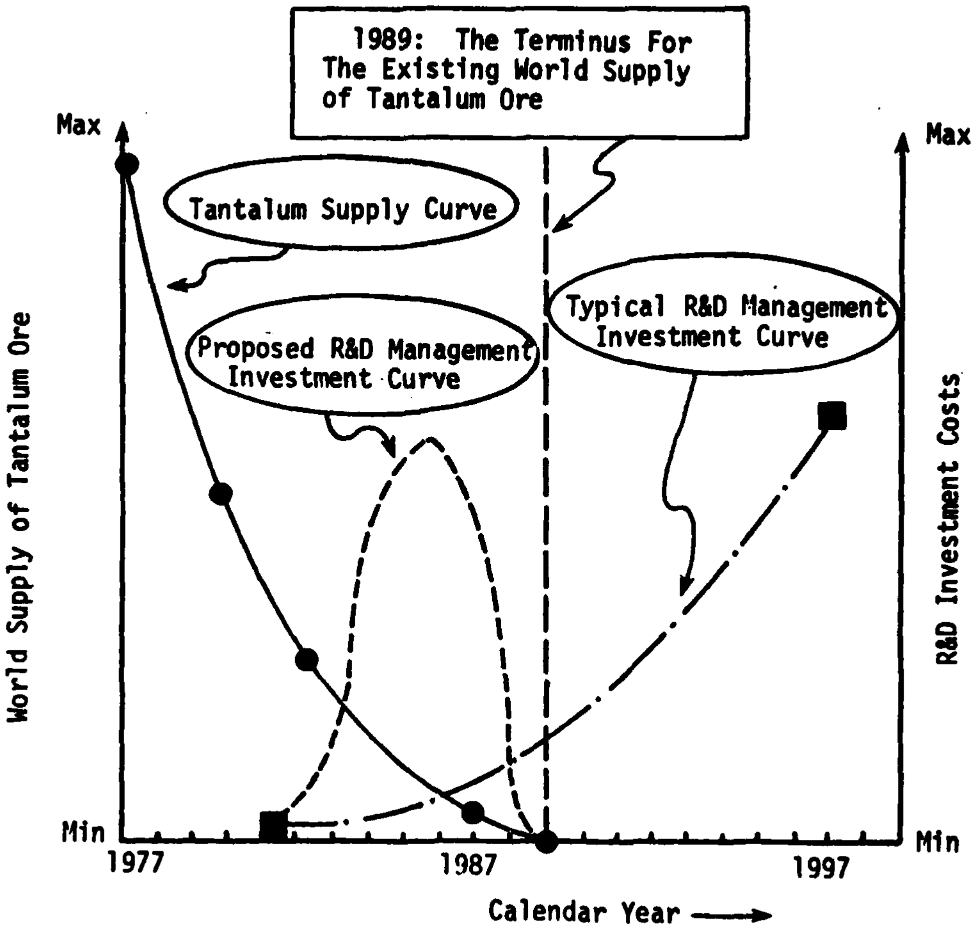


Figure 12. What is Needed *Now* to Eliminate the Tantalum Metals Crisis.

ELEMENT	SHORT TONS
MAJOR	
IRON	46 400 000
COPPER	473 000
ALUMINUM	250 000
CHROMIUM	60 000
NICKEL	73 900
MAGNESIUM	2 700
TITANIUM	--------
MINOR	
TIN	13 000
TUNGSTEN	250
COBALT	65
TANTALUM	62
PLATINUM GROUP	10

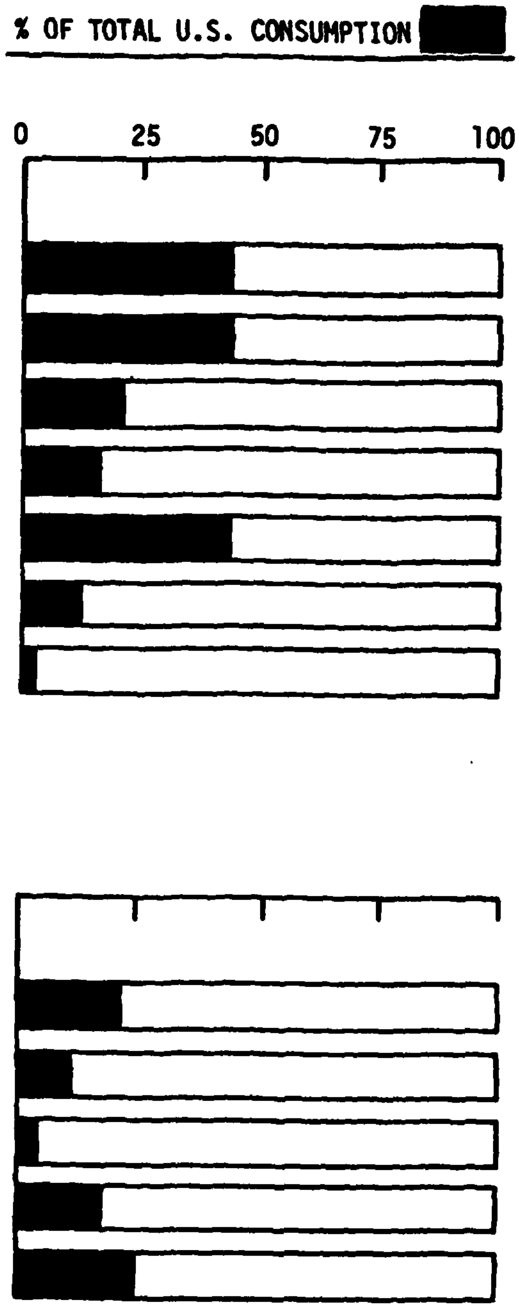
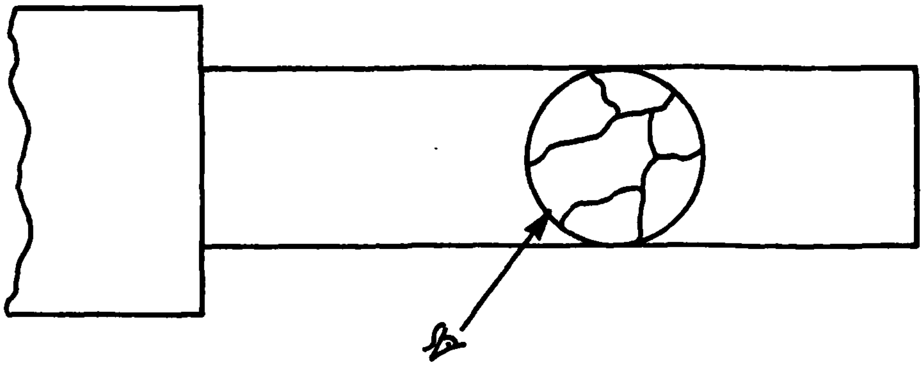
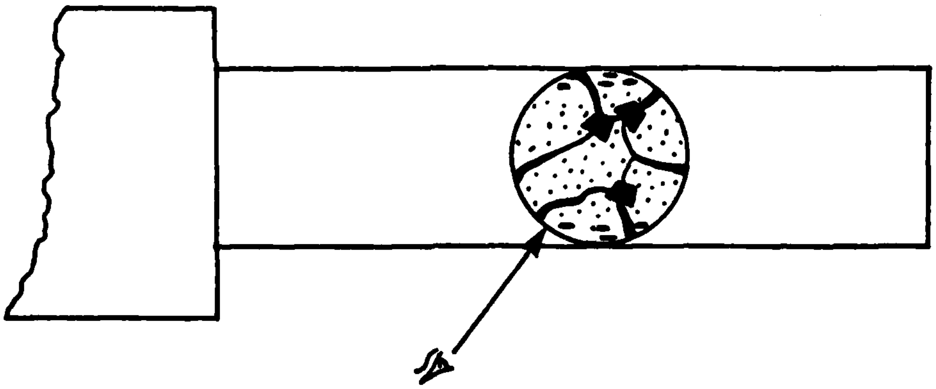


Figure 13. U.S. Consumption of "Old Material"
(Taken from Reference 9)



a) The Microscopic Appearance of "New Material".



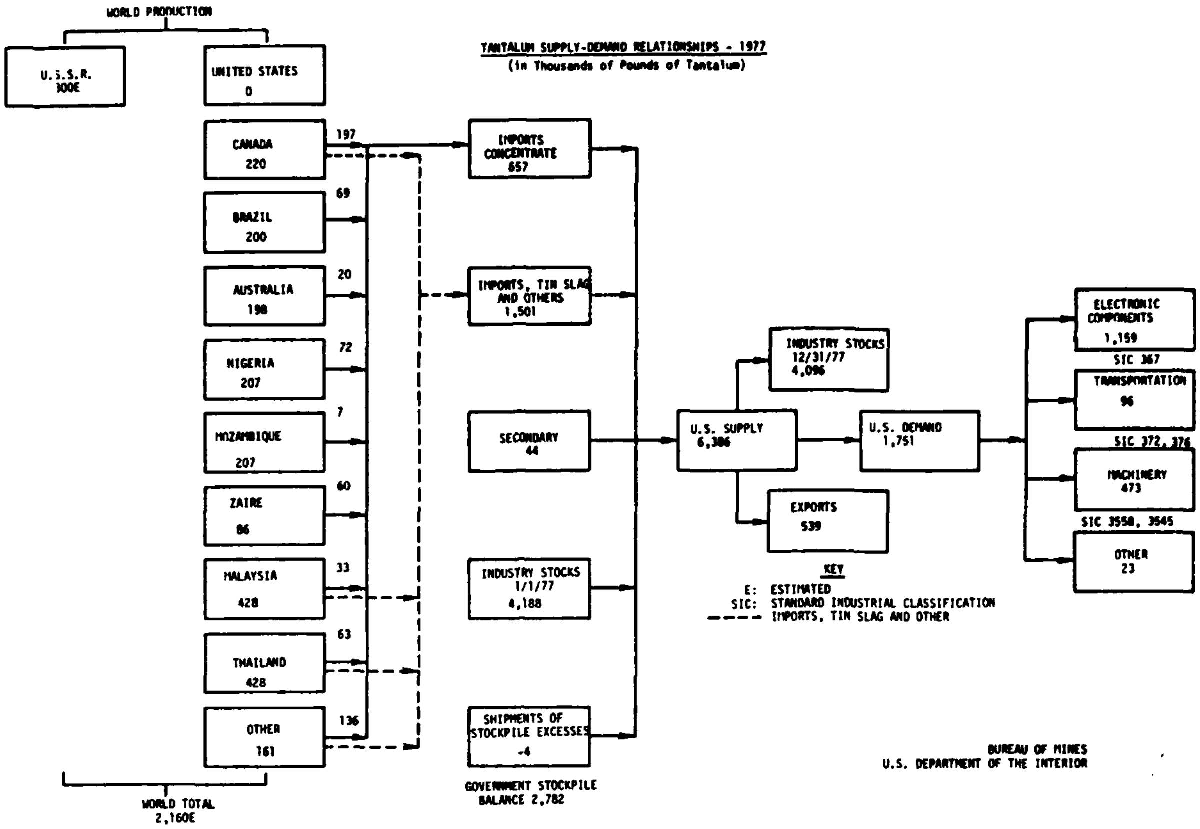
b) The Microscopic Appearance of "Old Material"

Figure 14. The Problem of Recycling "Old" Jet Turbine Blades - Exaggerated to Demonstrate the Difficulty of Metallurgical Recovery.

TABLE I. THE PROBLEM OF U.S. RESERVES

U.S. RESERVES	Importance to *all* Aerospace needs	
	Major	Minor
ABUNDANT	Copper Iron Magnesium Titanium	Molybdenum Thorium Vanadium Tungsten Zirconium
SCARCE	Aluminum Chromium Nickel	Tantalum Cobalt Columbium Manganese Tin Beryllium Platinum Osmium Ruthenium Iridium

TABLE II. TANTALUM* SUPPLY-DEMAND



TANTALUM SUPPLY-DEMAND RELATIONSHIPS, 1968-77
(Thousand pounds)

	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
World mine production										
United States	0	0	0	0	0	0	0	0	0	0
Rest of world	2,400	2,001	1,591	1,999	1,868	1,991	1,930	1,780	2,000	2,160
Total	2,400	2,001	1,591	1,999	1,868	1,991	1,930	1,780	2,000	2,160
Components of U.S. supply										
Domestic mines.	0	0	0	0	0	0	0	0	0	0
Secondary	[e]10	[e]35	[e]25	[e]30	[e]40	[e]40	[e]50	[e]5	[e]50	44
Government releases	150	215	162	6	88	266	884	87	8	[1](4)
Imports[2]	1,660	962	967	1,023	1,157	1,248	1,730	933	1,310	2,158
Industry stocks, Jan. 1	4,187	4,614	4,287	5,063	4,740	4,254	3,983	4,214	4,591	4,188
Total U.S. Supply	6,007	5,826	5,441	6,122	6,025	5,808	6,647	5,239	5,959	6,386
Distribution of U.S. supply										
Industry stocks, Dec. 31	4,614	4,287	5,063	4,740	4,254	3,983	4,214	4,591	4,188	4,096
Exports	210	230	234	201	250	322	435	428	443	539
Government accessions	693	18	0	0	0	0	0	0	0	0
Industrial demand	490	1,291	[3]903	1,181	1,521	1,503	1,998	220	1,328	1,751
U.S. demand pattern										
Electronic components	214	598	420	547	820	967	1,376	138	962	1,159
Transportation	182	349	211	257	254	150	156	14	69	96
Machinery										
Chemical equipment	19	55	73	89	132	96	98	24	102	161
Metalworking machinery	53	253	166	233	256	269	322	38	97	312
Total	72	308	239	322	188	365	420	62	199	473
Other	22	36	33	55	59	21	46	6	98	23
Total U.S. primary demand (industrial demand less secondary)	480	1,256	878	1,151	1,481	1,463	1,948	215	1,278	1,707

[e]Estimated
[1]Net change in inventory report
[2]Includes concentrates, tin slag and other.
[3]Adjusted to reflect revision in industry stocks.

*(Taken from Reference 61)

TABLE III. WORLD RESOURCES OF TANTALUM IN METRIC TONS OF Ta_2O_5*

Location	Resources Currently in Production			
	In Tin Ore	Independent of Tin Ore	Total	Life in Years (1)
Australia	160	----	160	2
Malaysia	2,250	1,100	3,350	21
Thailand	4,500	--	4,500	15
Nigeria	500	100	600	9
Zaire	1,800	---	1,800	40
Rwanda	50	---	50	11
Mozambique	---	500	500	7
Rhodesia	N.A.	N.A.	N.A.	N.A.
South Africa	---	20	20	10
South West Africa	400	---	400	
Brazil	450	---	450	4
Canada	---	550	550	4
Spain and Portugal	500	---	500	11
Egypt	---	---	---	---
Total	10,610	2,270	12,880	12 (2)

(1) Estimate at end 1977

(2) At 1977 production rate.

N.A. = Not Available

*(Taken from Reference 62)

Part II:

Technology Assessment
Concerning the Current Status of
Alloy and Coating Development Programs
For Refractory Metal Systems
Containing Cb, Mo, Ta and W

ABSTRACT

Because of an ever increasing demand for improved materials with better serviceability at higher operating temperatures, this report evaluates the literature on Cb, Mo, Ta and W to determine the status for alloy development and coating development programs. Although of short duration and limited scope, this report reviews the work done on refractory alloys and coatings through collective examinations for greater dissemination of information that is not, generally, well known. The detailed findings of a massive Computer-Aided-Literature search are presented and specific recommendations are also given.

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INTRODUCTION

Because of an ever increasing demand for improved materials that will provide better serviceability at higher operating temperatures, much attention has recently been given to the metallurgical design variables for the refractory metals columbium, molybdenum, tantalum and tungsten.

During the early years of jet aviation, the turbine sections of aircraft engines utilized superalloys of nickel and cobalt with about 20 weight percent chromium. These high chromium contents were necessary to withstand the rigorous demands of hot strength and oxidation resistance for turbines where inlet temperatures were controlled at less than about 1600°F. With the advent of hotter engines and the attendant depletion of chromium supplies, metallurgists developed stronger superalloys by increasing the aluminum and titanium contents needed to form greater hot strengths via the mechanism of more gamma prime (γ') precipitates. In other words, more γ' was introduced so that less chromium would be required for aircraft engine purposes. This design trend toward the use of more γ' produced a new generation of strong superalloys (containing about 10 weight percent chromium) that were serviceable at higher turbine temperatures without a significant loss in strength-at-temperature. Unfortunately, these new superalloys with lower chromium content offered poor oxidation resistance at the higher operating temperatures. In an effort to alleviate this problem of inadequate corrosion behavior, much research was given to the task of developing new coatings for inlet turbine temperatures of about 2200°F. These new coatings, typically aluminides or silicides, provided acceptable oxidation and sulfidation resistance at the higher service temperature through the adept use of bypass-air-cooling-design approaches.

At the present time, modern military aircraft engines require structural alloys that can operate for optimum intervals of time at temperature limits of about 2500°F. The refractory metals of columbium (Cb), molybdenum (Mo), tantalum (Ta) and tungsten (W) offer an excellent basis for development of advanced turbine blade and rotor systems but, unfortunately, the state-of-the-art is not well developed for this family of metallurgical materials. In 1966, the National Materials Advisory Board (NMAB) published guidance concerning the fabrication of refractory metal sheet for application on glide re-entry and hypersonic aerospace vehicles.(1) In 1970, the NMAB released another classic report on coatings for the protection of superalloys, refractory metals and graphite from oxidation at temperatures of 2000 to 3000°F.(2) During the 1970s , some research has been done on the problem of using more refractory alloys in Military applications, e.g.:

- Solar International of San Diego has done work for the U.S. Army regarding coatings for columbium airfoils.(3)
- Teledyne CAE of Toledo has established new columbium rotor materials for the U.S. Air Force.(4)
- Rohr Aviation of Chula Vista has developed Cb nozzles for critical USAF Missile applications.(5)
- Hi-Temp Company of Long Island continues to work on refractory alloy coatings.(6)
- NASA's Lewis Research Center of Cleveland has done continual research toward development of improved aerospace alloys containing Cb, Mo, Ta and W.(7)

This is to say that, although much work has been done on refractory alloys and coatings during the 1970s, these research findings have not been collectively examined in detail and the associated information has not been disseminated to any great extent. The purpose of this report is to examine the literature on the refractory metals Cb, Mo, Ta and W for a determination of the following:

- Alloy Development Status
- Coating Development Status

Although of short duration and limited scope, this study attempts to focus on the metallurgical design problems that face the aerospace needs and priorties of now and during the near-term future. Specific recommendations are to be given with the hope that such suggestions might motivate some definite development programs for solving the problems that will exist for future aerospace systems containing refractory alloys and their coatings.

Experimental Design

Figure 1 of the Appendix section reveals the basic approaches that were undertaken to address the objectives of this Summer Research Assignment for the concomitant interests of dual sponsors; viz., The Southeastern Center for Electrical Engineering Education (SCEEE) and the Air Force Materials Laboratory (AFML) at Wright-Patterson Air Force Base, Ohio (WPAFB). Here it is to be seen that this experiment was approached through the modern methodology of Integrated Computer-Aided Manufacturing (ICAM) via some influence by ICAM's Definition Methods; i.e., IDEF.[8]

Basically, the experimental design of inputs, outputs, controls and mechanisms was structured according to the following activity outline:

Technology Assessment (TA) Goals and Approaches

Input to TA Function

- DDC Literature Survey
- Information Analyses
- Survey of Research Funding Agencies
- Data Reduction Relative to Research Objectives

Output of TA Function

- A Written Report for Information Transfer
- Important Study Areas are Highlighted
- Possible Research Programs are Recommended

Controls for TA Function

- Within the Guidelines and Restrictions of SCEEE
- As Directed by The WPAFB Focal Point Project Monitor (Mr. H. A. Johnson)

Mechanisms for TA Function

- Reading
- Reviewing
- Reporting

Figure 2 shows the experimental design logic which was used to maximize the efficiency of the Computer-Aided-Literature search. Here it is to be noted that only literature retrievals from the reaction zones (Metal-Alloys, Alloys-Coatings and Metal-Coatings) were evaluated from search targets that involved Cb, Mo, Ta and W metals or alloys/coatings thereof. In this way, the massive literature search was appropriately optimized.

DISCUSSION OF RESULTS

The results of this research activity are grouped into, essentially, two parts and these include (1) The Defense Documentation Center (DDC) literature search and (2) A metallurgical evaluation of these Computer-Aided-Literature-Findings (CALF) per the expressed interests of alloy and coating development status reports.

The DDC Literature Search

Figure 3 shows how the two areas of alloy development and coating development have been divided during the years between 1970-1979. Here it is to be seen that research funding by the U.S. Military is about equally divided between these two important technological objectives... coating development studies received 54 percent of the funding and alloy development studies obtained 46 percent. If this activity is analyzed further, the data of Figure 4 are available to offer these observations...

- For research on columbium, the U.S. Military have dedicated 51 percent of their topical funding toward coating development studies and 49 percent toward work on alloy development.
- For research on molybdenum, the U.S. Military have distributed their funding in this manner... 57 percent on coatings and 43 percent on alloys.
- For research on tantalum, the U.S. Military have spread the funds thusly... 52 percent on coatings and 48 percent on alloys.
- For research on tungsten, the U.S. Military have apportioned their associated funding to achieve 54 percent of the funds on coating studies with 46 percent given to the establishment of tungsten alloy research.

Although these statistics are not of individual importance, the data of Figures 3 and 4 depict an important and consistent trend... in every case, the U.S. Military have given more attention to coating development than that which has been dedicated to alloy development studies.

Obviously, this trend provokes the usual controversy... is it proper to spend more money on new coatings at the expense of alloy development? In reality, this argument is a difficult one to present because coatings are as necessary as alloys and *vice versa*. Because the projected requirements for future aerospace engine systems are a clear mandate for improved refractory alloys and because a coating cannot be tailored until the alloy is first obtained, the position of this author is fixed thereby... *it is wrong to spend more money on coatings*. This is to say that hotter engines of the 1980s will never exist if the U.S. Military continue to develop *new coatings for old alloys* instead of developing *new alloys and new coatings*. In this particular case, the percent difference in funding between coatings vs. alloys is not so large such that any issues must be treated on the basis of general principles, not factual differences.

Figure 5 indicates how the research funding on alloy development and coating studies has been distributed among the Military for the period between 1970-1979. These data indicate the following:

- For research on columbium alloys and coatings, the funding trend is of this order - Air Force (74%), Army (20%) and Navy (6%).
- For research on molybdenum alloys and coatings, the funding is divided in this way - Air Force (50%), Army (27%) and Navy (23%).
- For research on tantalum alloys and coatings, the Air Force supports 61 percent, the Army 33 percent and the Navy supports only 6 percent.
- For research on tungsten alloys and coatings, the funding distribution is more uniform; Air Force (45%), Army (42%) and Navy (13%).

Again, these statistics are not of real significance if reviewed on a singular basis. Collectively, however, these data demonstrate an important, consistent trend... in all instances, the U.S. Air Force has carried the burden for most funding responsibility on alloy/coating oriented research conerning Cb, Mo, Ta and W.

This consistent trend of maximum apportionment by the Air Force introduces an obvious issue... is it correct for the Air Force to assume this financial burden? The answer to this issue is equally obvious... if the Air Force won't, who will? The critical/strategic needs and priorities of the Air Force can best be treated *by* the Air Force and *for* the Air Force. The hotter aircraft engines of the 1980s will never exist unless alloy development and coating development continue to represent vital segments of the Air Force funding activity.

Figures 6 through 9 are control chart studies which depict how the funding on alloy development research has varied among the Military for the past decade. The data offer the following observations:

- For research on columbium alloy development, the ten-year trend is about stable but 1979 represents a period of decline as compared to the largest funding years of 1977 and 1978.
- For research on molybdenum alloy development, the ten-year trend is about stable but 1979 represents a period of decline if compared to the maximum funding year of 1978.
- For research on tantalum alloy development, the ten-year tend is definitely negative (decreasing with time) and 1979 represents the worst year for funding that this category has ever realized.

- For research on tungsten alloy development, the ten-year trend is about stable but 1979 represents a period of decline as compared to the larger funding year of 1977.

These statistics suggest that the ten-year trend for alloy development funding is, generally, stable but it must be mentioned that more work is needed on tantalum alloy research.

Figures 10 through 13 are similar control chart studies except that the funding trends for coating development studies by the Military for 1970-79 are displayed, instead. These data offer the following observations:

- For research on columbium coating development, the ten-year trend is definitely negative (decreases with time) and 1979 represents the worst funding level that this category has ever achieved.
- For research on molybdenum coating development, the ten-year trend is slightly negative and 1979 represents the worst funding level ever achieved.
- For research on tantalum coating development, the ten-year trend is generally, negative if compared to the peak funding years that initiated this decade (1970 and 1971). Again, 1979 represents a period of decline and the worst funding level for the whole decade.
- For research on tungsten coating development, the ten-year trend is about stable but 1979 represents a period of decline and the worst funding level for the entire decade.

These statistics suggest that the ten-year trend for coating development funding is, generally, negative and it must be stated that more work is needed on coating research for Cb, Mo, Ta and W; particularly if the "bad-year" of 1979 is appropriately considered.

Status of Alloy Development

If 73 of the 98 atomic elements are classified as metallic, then the alloy development situation for Cb, Mo, Ta and W is, in the main, undeveloped. Table I reveals that these refractory elements have 26 phase diagrams which have not yet been developed or are mired in controversy. This is to say that more than one-fourth of all atomic elements (26/98) have not been properly evaluated by alloy development researchers. The alloy development needs for Cb-X, Mo-X, Ta-X and W-X are of this order; Ta, Cb, Mo and W...

- Twenty-two (22) phase diagrams for Ta-X are in dispute.
- Seventeen (17) phase diagrams for Cb-X are in dispute.
- Sixteen (16) phase diagrams for Mo-X are in dispute.
- Fifteen (15) phase diagrams for W-X are in dispute.

Furthermore, it needs to be pointed out that, if ternary phase diagrams are also considered, the alloy development situation is even more insidious. Table II reveals that this Computer-Aided-Literature search discovered evidence indicating that only 54 ternary phase diagrams have been properly determined for Cb-, Mo-, Ta- and W-base alloy systems. The significance of this finding is lost without proper explanation.

Table I indicated that 47 metallic elements (73 - 26 = 47) had been properly evaluated because 26 had not... the assumption is that all atomic elements of Table I offer metallic properties if selectively alloyed. On this basis and considering the traditional equation for possible combinations of (n and r); viz.,

$$\binom{n}{r} = \frac{n!}{(r!)\ (n-r)!}$$

where (n = 47) and (r = 3), then

$$\binom{47}{3} = \frac{47!}{(3!)\ (44!)} = 16{,}215.$$

This is to say that, for 47 atomic elements, 16,215 viable ternary systems could exist but only 54 where discovered by this Computer-Aided-Literature search. In other words, 54 ternary alloy systems represent only about 0.3% of the viable total... the ternary alloy development situation for Cb, Mo, Ta and W is certainly underdeveloped. In summary here, the data of Tables I and II suggest that very little has been done and very much remains to be done.

An overview statement for the alloy development situation would require words to the effect that more funding must be given to the problem of alloy development for Cb, Mo, Ta and W alloy systems - binary, ternary and quaternary. Specifically, it must be stated that certain columbium and molybdenum alloys are now available or soon will be in the immediate future. Many of these alloys exhibit known and serious metallurgical design limitations, however. Specifically, it is a truism that the development of tantalum and tungsten alloys is still at a very early stage - somewhere between infancy and adolescence. Research and development for producing new alloys of all four metals is badly needed for the hotter Military engines of the 1980's. Although it is unlikely that a single alloy will be discovered to satisfy all metallurgical design requirements, it is imperative that these technical objectives should be addressed: viz.,

- Alloys must be developed with improved strength at elevated temperatures. Here, the research needs to be directed at achieving higher Recrystallization Temperatures (T_{RX}).

These design characteristics yield a complex problem that is of great interest to the Military needs and priorities of our Nation.

Figures 18 through 21 illustrate certain basic problems that threaten the status of coating development studies for Cb, Mo, Ta and W substrates. These data offer the following observations:

- For coatings, endurance (protective life) varies inversely with the service temperature.
- For coatings, strength (yield) varies inversely with the service temperature.
- For coatings, ductility (tensile elongation) varies directly with the service temperature.
- For coatings, corrosion control varies inversely with fatigue control.
- For coatings, erosion properties vary inversely with the ablative properties.

These illustrations demonstrate that the problem of coatings is always quite difficult, but what is the status of today's coating development activity?

Figures 22 and 23 give some indication about the existing technology; viz.,

- Coatings for molybdenum substrates offer a state-of-the-art that looks promising for turbine inlet temperatures of about 2500°F. Here, the likely candidates are silicides or Al-Cr-Si Compounds.

- Alloys must be developed with a definite improvement in oxidation resistance. Here, the research needs to be directed toward passivity; i.e., high-chromium-type alloys must be obtained through chromium-substitutes, not chromium.
- Alloys must be developed with marked improvement in workability and formability. Here, the research needs to be directed toward an enhancement of the Ductile-Brittle Transition Temperatures (T_{DB}).
- Alloys must be developed with better creep properties. Here, the research needs to be given to an appropriate dis- placement of the Equicohesive Temperatures (T_{EQ}).

Inasmuch as may be possible, this proposed research on *better alloys for better engines* should be dedicated to all factors that influence the different aspects of modern metallurgical design. See Figures 14 through 17 for typical trends.

Status of Coating Development

As summarized by Hausner [9], the different problems for successful coating of metals are extremely complex. An acceptable coating should offer these important characteristics:

- The coating must serve as an effective air barrier,
- The coating must exhibit the optimum advantages of modern metallurgical design,
- The process of coating must ensure continuity and adherence in layering,
- The coating must offer physical and chemical stability, and
- The coating interface between the layer and its substrate must undergo physical or mechanical bonding reactions.

- Coatings for Cb, Mo, Ta and W substrates (collectively) will require development if long service periods are desired. For serviceability in excess of about 1000-hours, the research must be given to coatings that are made from cermets, ceramics and unique alloys.

These data suggest that the current status of coating development appears acceptable for existing technology but *not* acceptable for the technological demands of hotter engines in the 1980s.

The next obvious issue deals with the question, what can be done to improve the status of coating development? A simplistic answer to this issue would be of the form... because so little has been done and, because so much must be done, *do more*. In support of the simplistic attitude, some discussion is now required.

Table III cites the results of several telephone interviews with different Government Agencies who are responsible for expanding the sum of total knowledge about new alloy and coating developments. Here, the following observations are to be given:

- Of the nine (9) Agencies that were surveyed, only two (2) of the nine (9) admitted that they supported alloy development research.
- Of the nine (9) Agencies that were surveyed, none of the nine (9) would admit that they supported any coating development research.

Clearly, very little is now being done... but what can be done?

In general terms, the literature indicates that the following activities need to be addressed:

- Characterization and evaluation methods for coatings are still classified as "old technology"... the techniques of dealing with coatings at the laboratory level badly need more sophistication through newer methods and appliances.
- Improvements in the processing of small crevices, large or complex shapes are badly needed.
- Because the prospect of discovering adequate coatings is not too probable (i.e., a low probability of success prevails), design concepts, metallurgical parameters and performance restrictions need complete re-evaluation.
- Coatings that form passive layers, amorphous structure and self-healing mechanisms require investigation.
- A fundamental understanding of the factors that govern the performance of coatings is needed for development of a sound basis for advanced coating systems. At this time, not enough is really known about *why coatings work* or *how coatings succeed* - here, significant advances are mandatory if real progress is to be achieved.

These activities will do much to advance the status of coatings and coating development programs but, specifically, what approach should be taken?

If the Military needs for advanced engines with turbine inlet temperatures of about 2500°F are to be satisfied, the data of Figure 24 must be evaluated in some detail; viz.,

- The research opportunity for better coatings must involve the elements Ru, Ir, Cr, Rh and Hf.
- The research opportunity to find a suitable substitute for chromium must involve hafnium.

- Coatings for Cb, Mo, Ta and W substrates (collectively) will require development if long service periods are desired. For serviceability in excess of about 1000-hours, the research must be given to coatings that are made from cermets, ceramics and unique alloys.

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Clearly, very little is now being done... but what can be done?

In general terms, the literature indicates that the following activities need to be addressed:

From a practical standpoint, it would seem that the most logical area in which to begin would involve hafnium... the Nation has large stockpiles of Hf metal and few apparent applications for Hf metal.

CONCLUSION

Because of an ever increasing demand for improved materials with better serviceability at higher operating temperatures, this report evaluates the literature on Cb, Mo, Ta and W to determine the status for alloy development and coating development programs. Although of short duration and limited scope, this report reviews the work done on refractory alloys and coatings through collective examinations for greater dissemination of information that is not, generally, well known. The detailed findings of a massive Computer-Aided-Literature search are presented and specific recommendations are also given.

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(8) "Architect's Manual on ICAM Definition Method (IDEF) - Version 0", Report, SofTech, Inc., Waltham, Mass., USAF Contract F33615-78-C-5158, October 1978.

(9) H. H. Hausner, "Coatings of High Temperature Materials", Book, Plenum Press, 296 Pgs, 1966.

(10) R. I. Jaffee and D. J. Maykuth, "Refractory Materials", DMIC Memorandum 44, February 1960.

APPENDIX

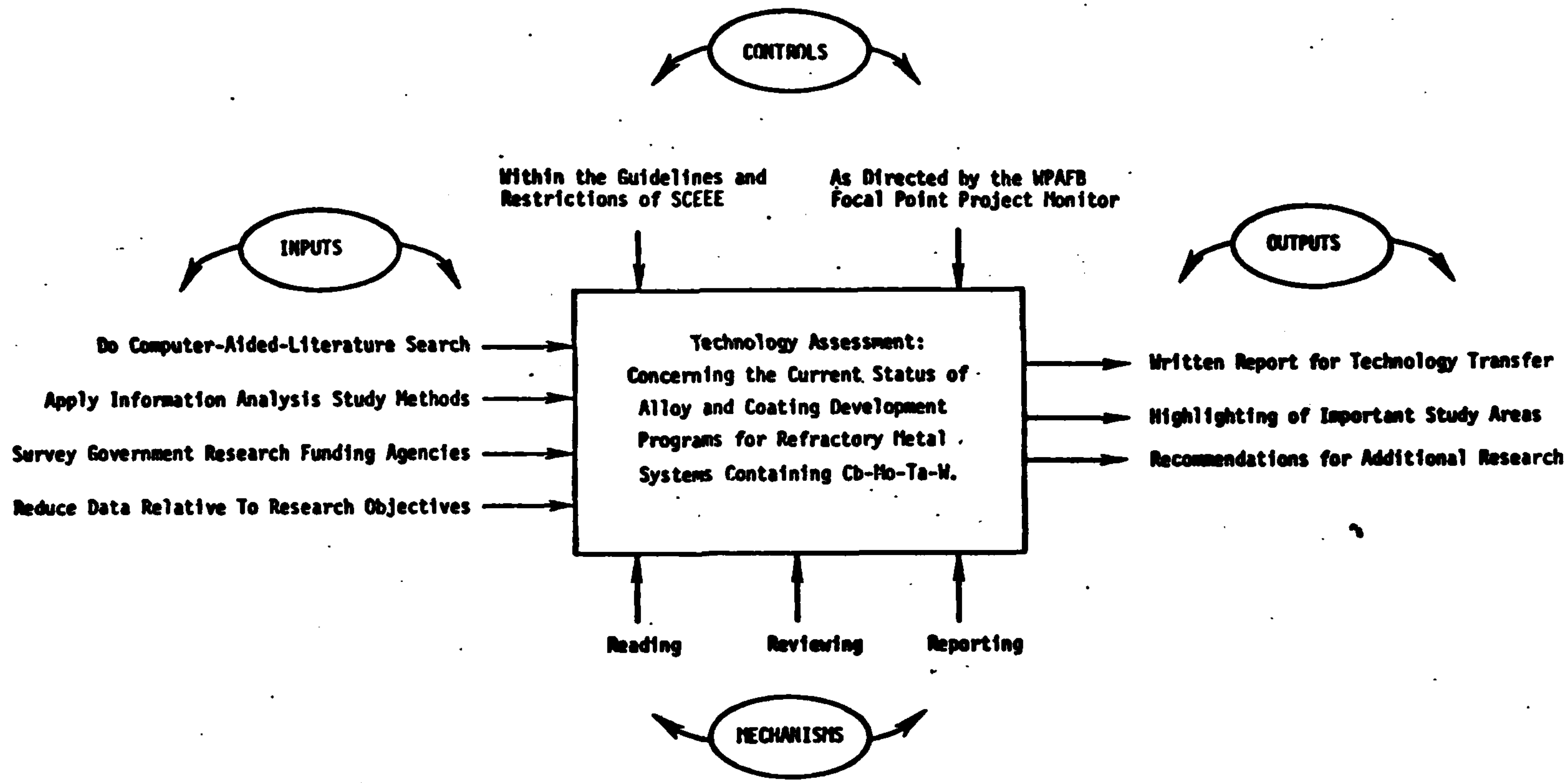


Figure 1 - Experimental Design for Summer Research Assignment.

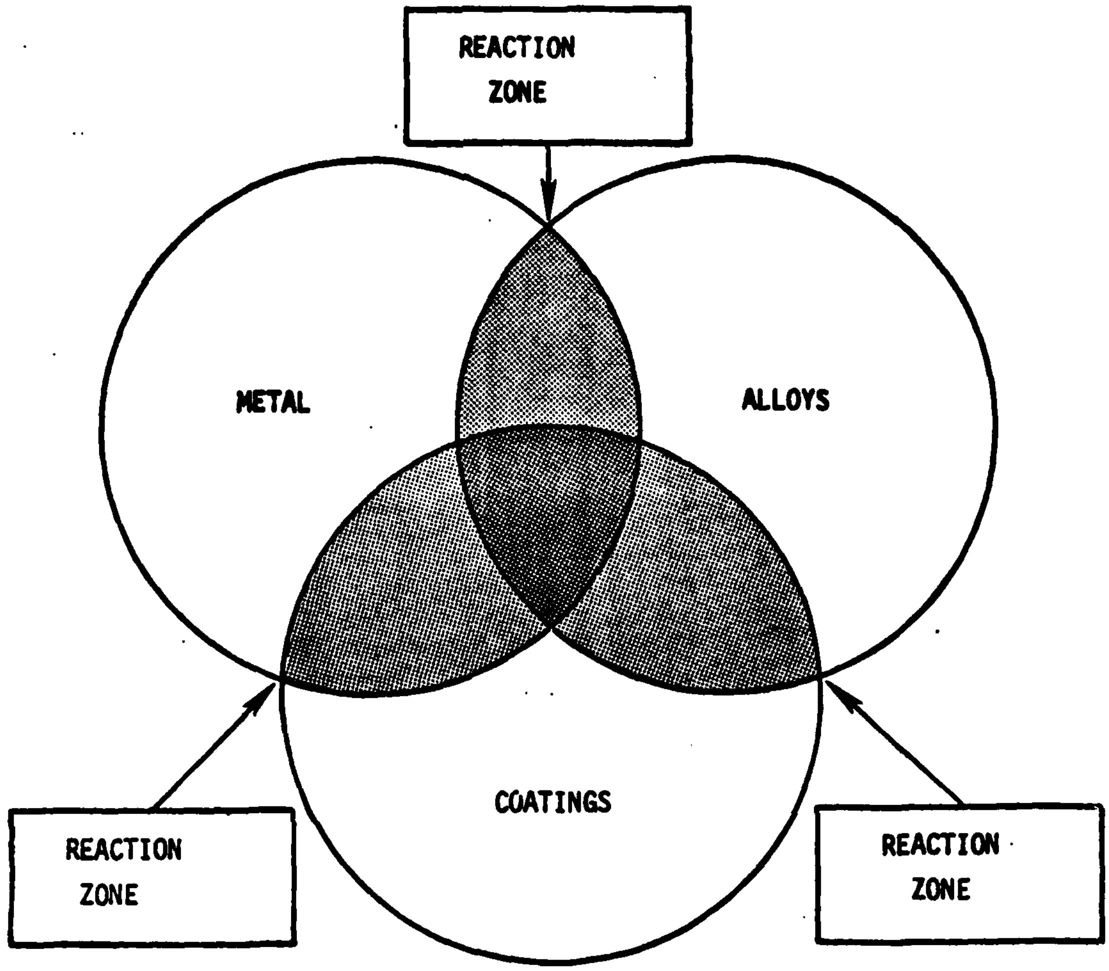


Figure 2 - A Sketch which Reveals the Targeting Approach Used by this Computerized Literature Search (Literature Retrievals from the Reaction Zones were used from Targets that Involved Cb, Mo, Ta and W Metals or Alloys/Coatings Thereof).

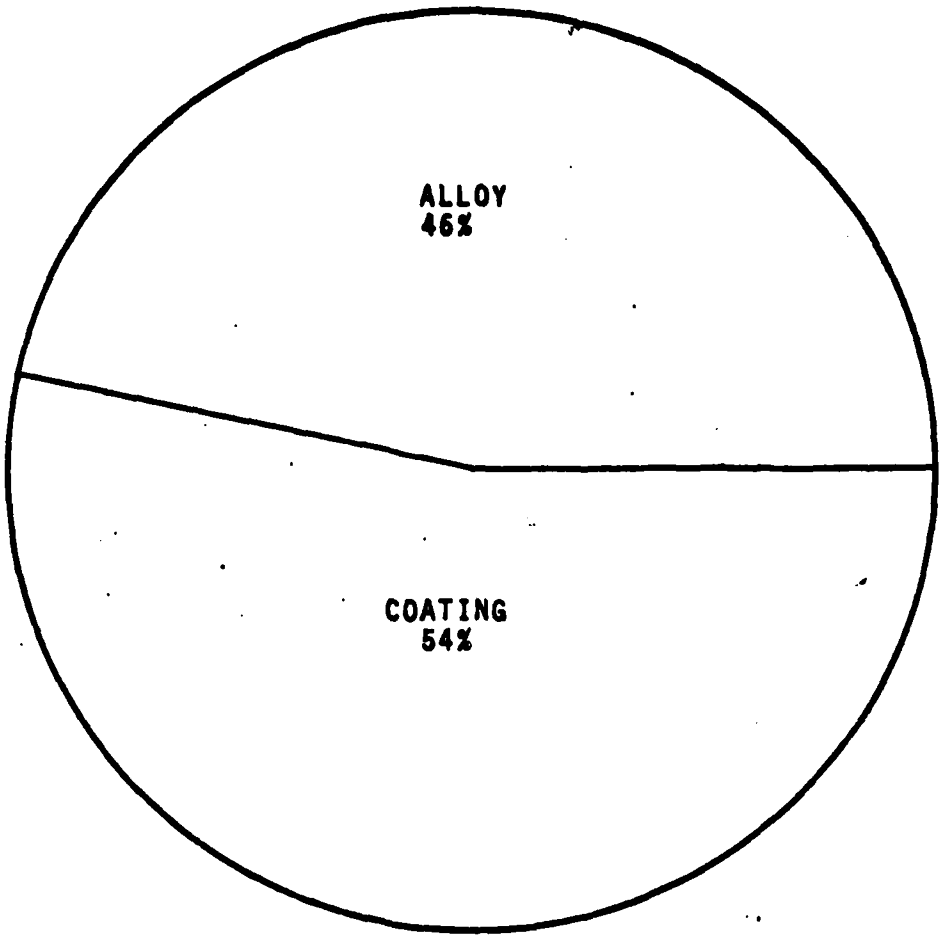


Figure 3 - Composite Structure for Research Funding by the U.S. Military on Alloy Development and Coating Studies (Cb, Mo, Ta and W).

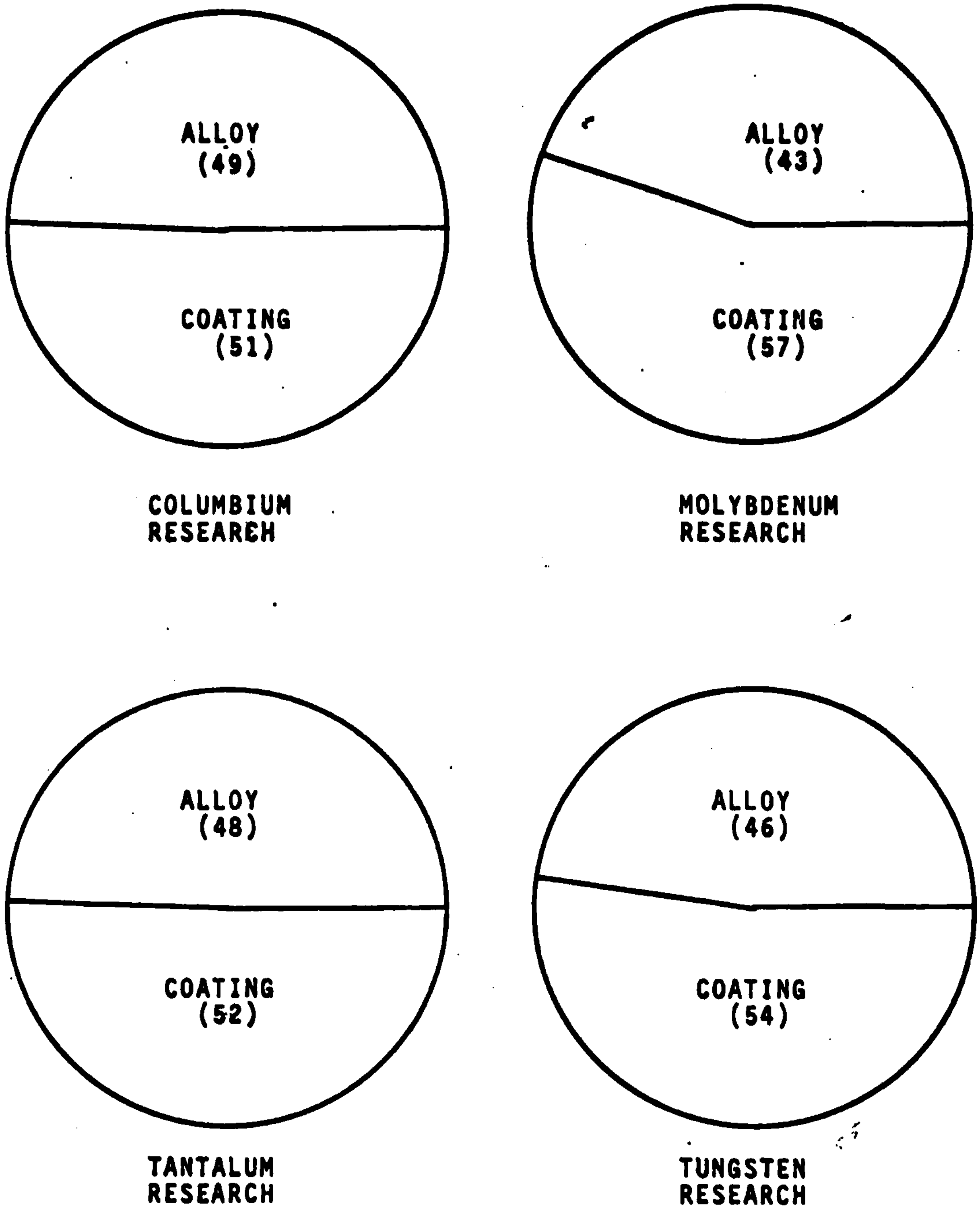


Figure 4 - Distribution of Research Funding by the U.S. Military on Alloy Development and Coating Studies.

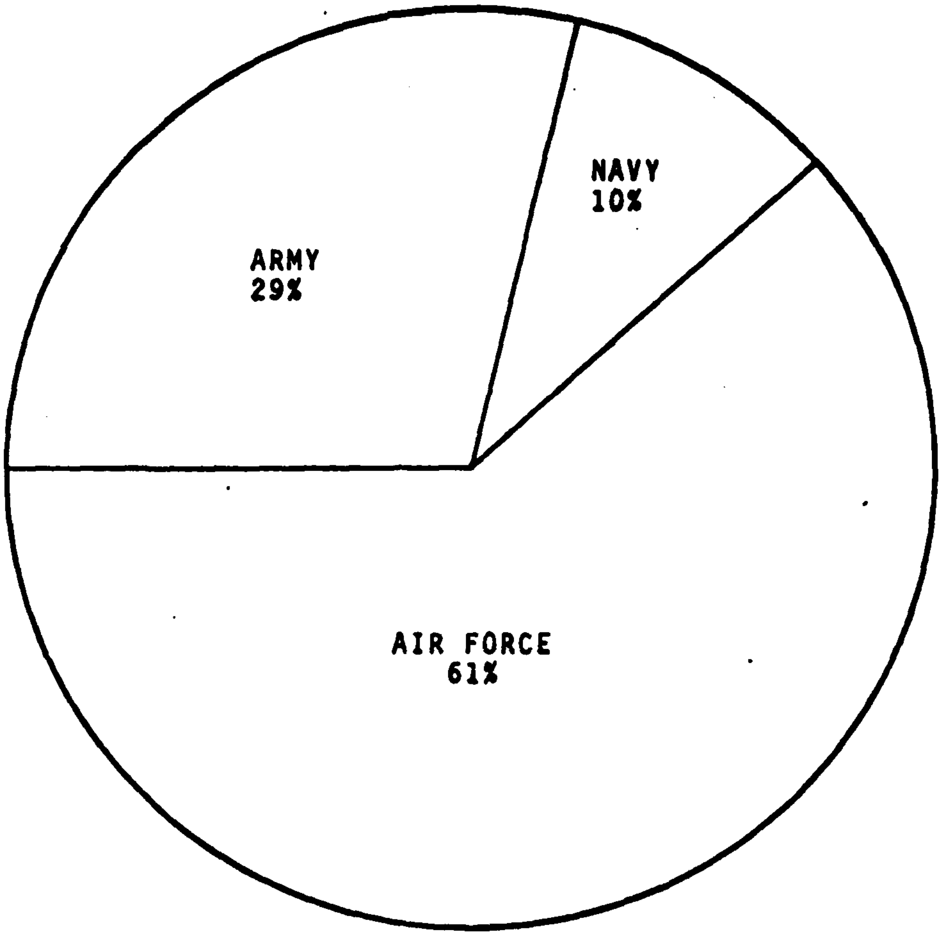


Figure 5a - Composite Structure for Research Funding by the U.S. Military on Alloy Development and Coating Studies (Cb, Mo, Ta and W).

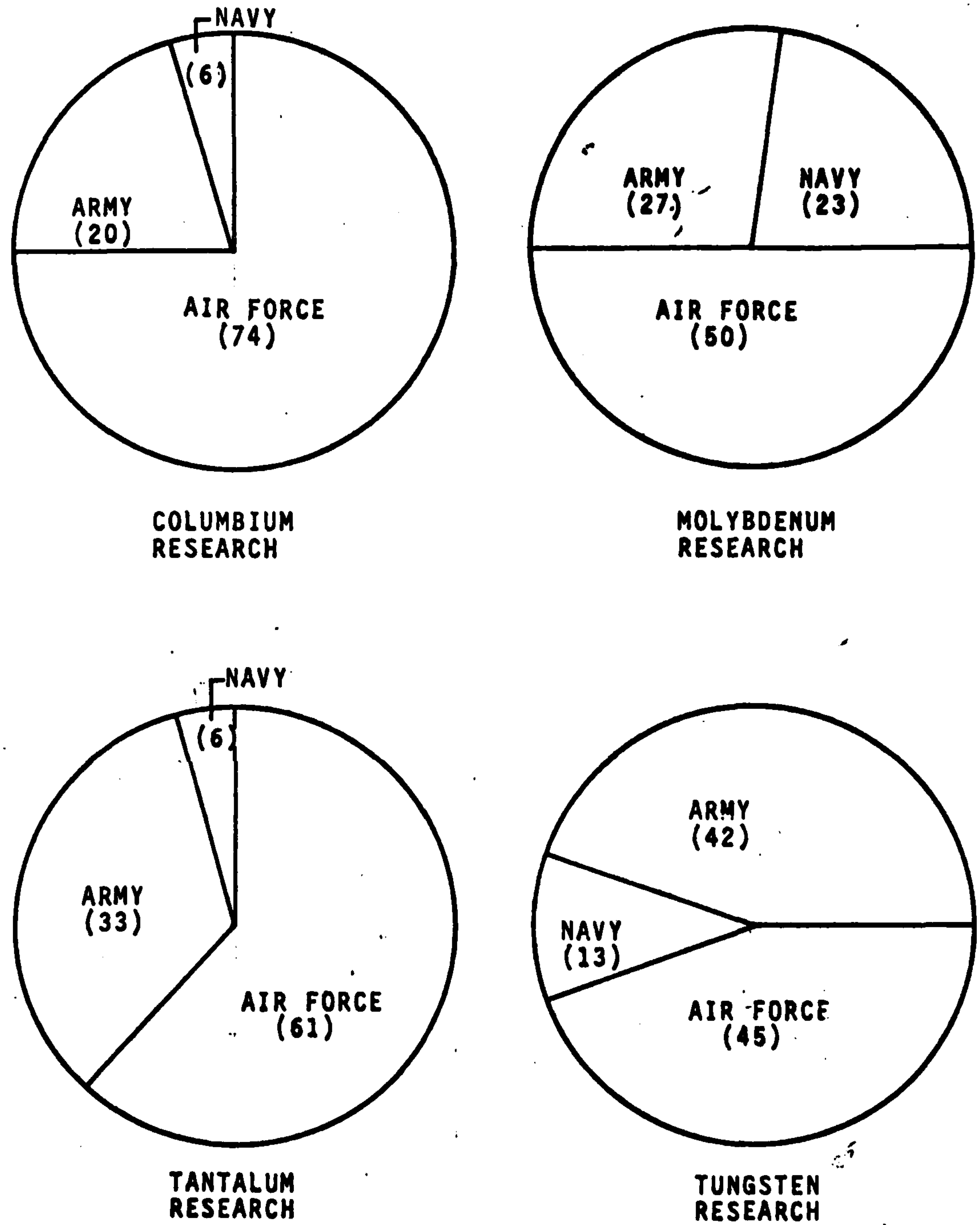


Figure 5b - Distribution of Research Funding by the U.S. Military on Alloy Development and Coating Studies.

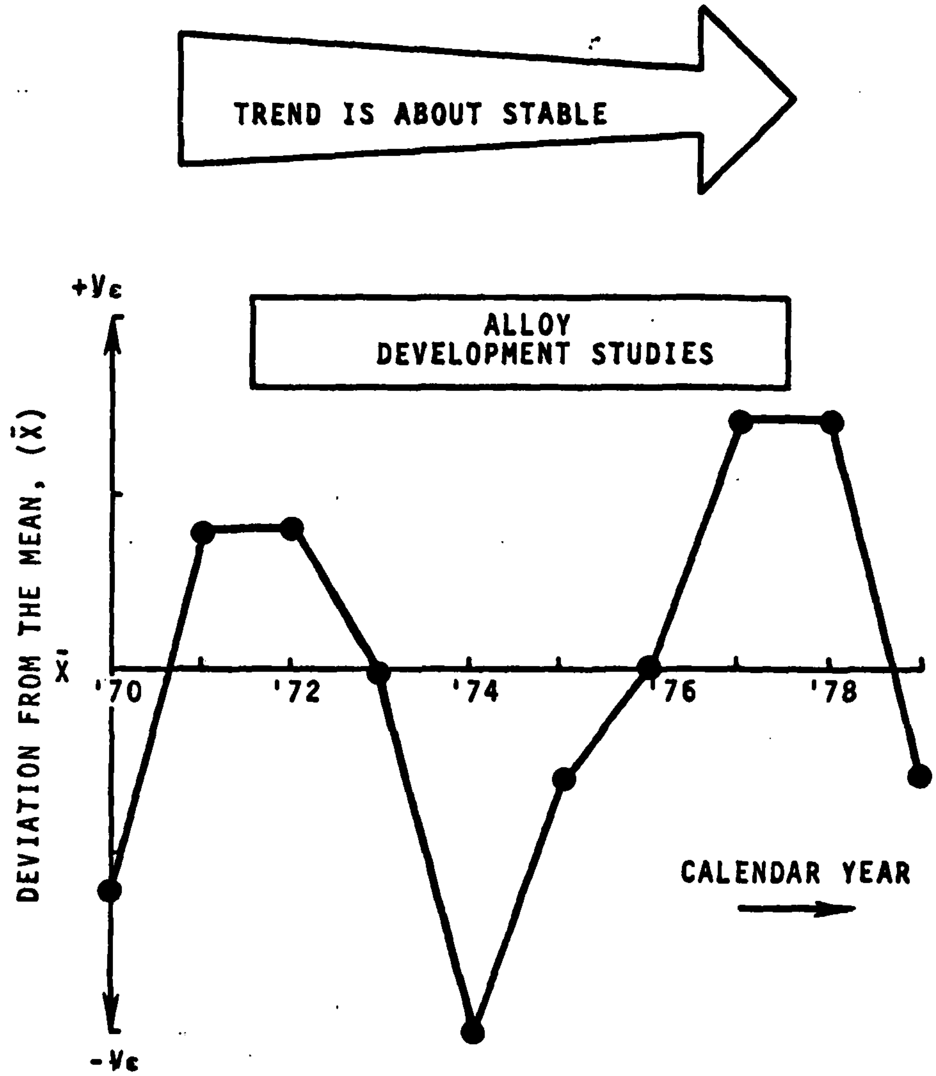


Figure 6 - Research Funding Trend by the U.S..Military for Alloy Development Studies on Columbium.

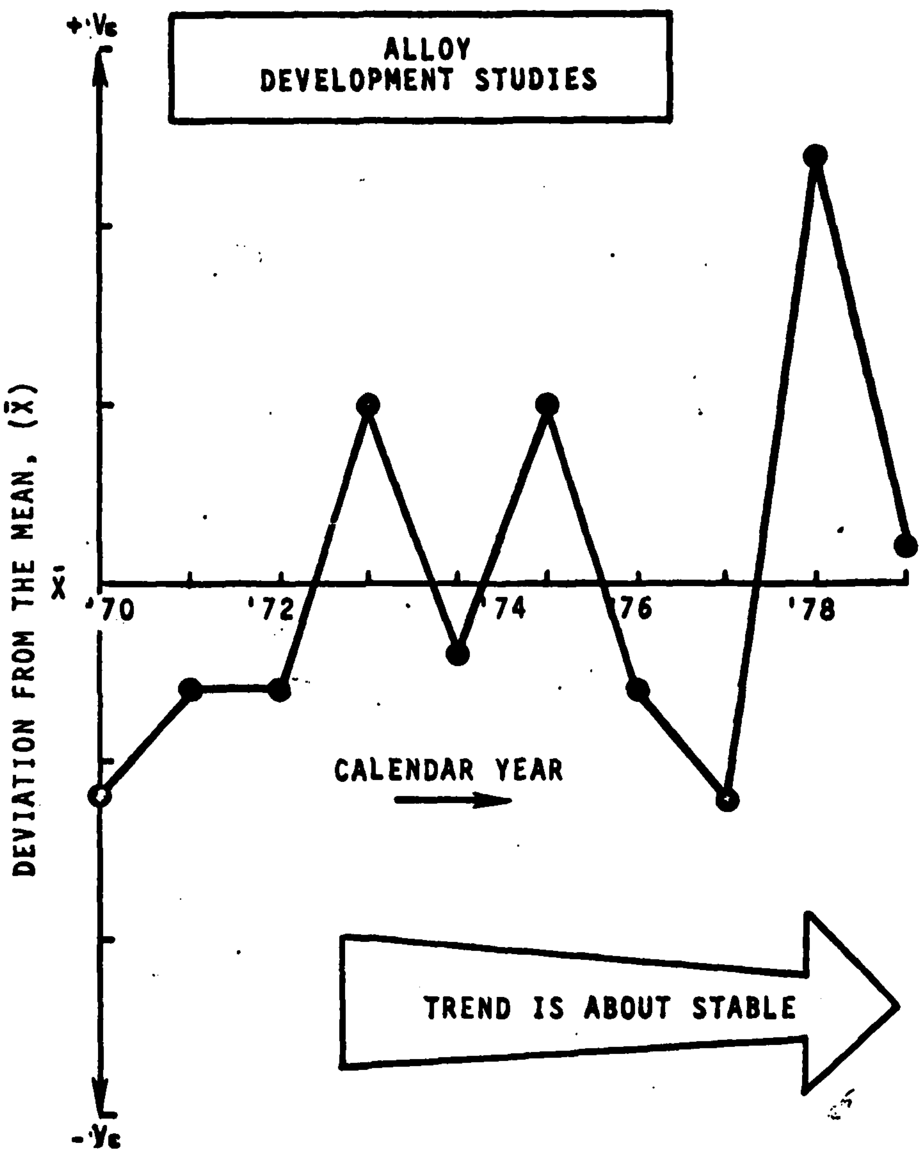


Figure 7 - Research Funding Trend by the U.S. Military for Alloy Development Studies on Molybdenum.

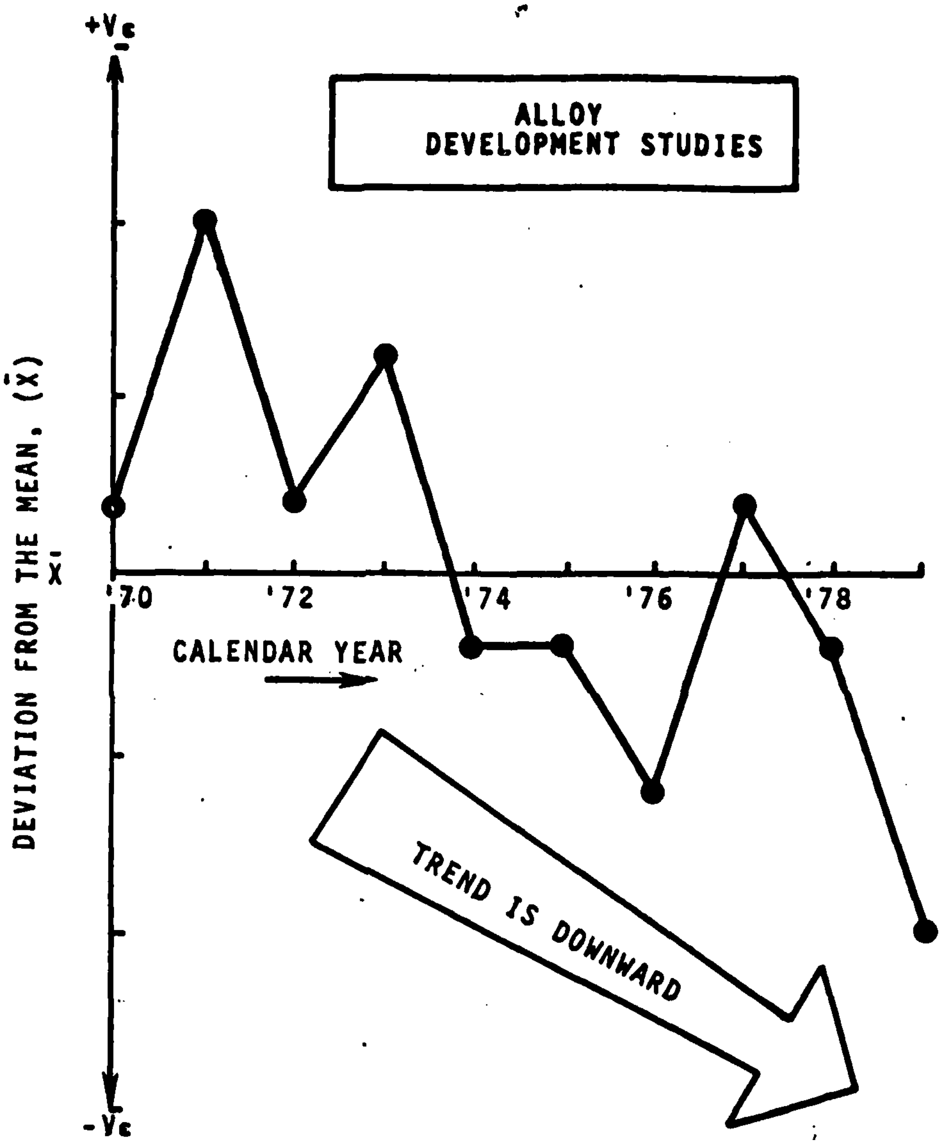


Figure 8 - Research Funding Trend by the U.S. Military for Alloy Development Studies on Tantalum.

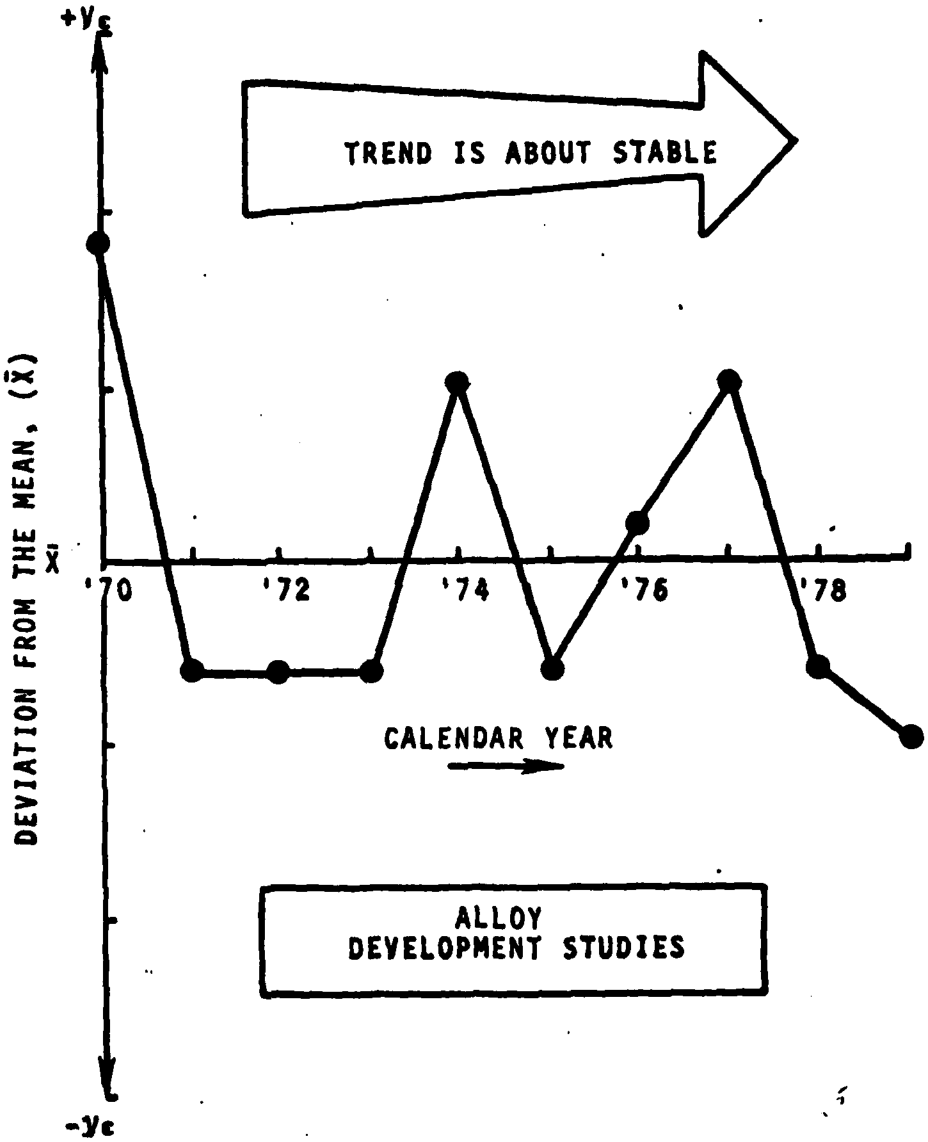


Figure 9 - Research Funding Trend by the U.S. Military for Alloy Development Studies on Tungsten.

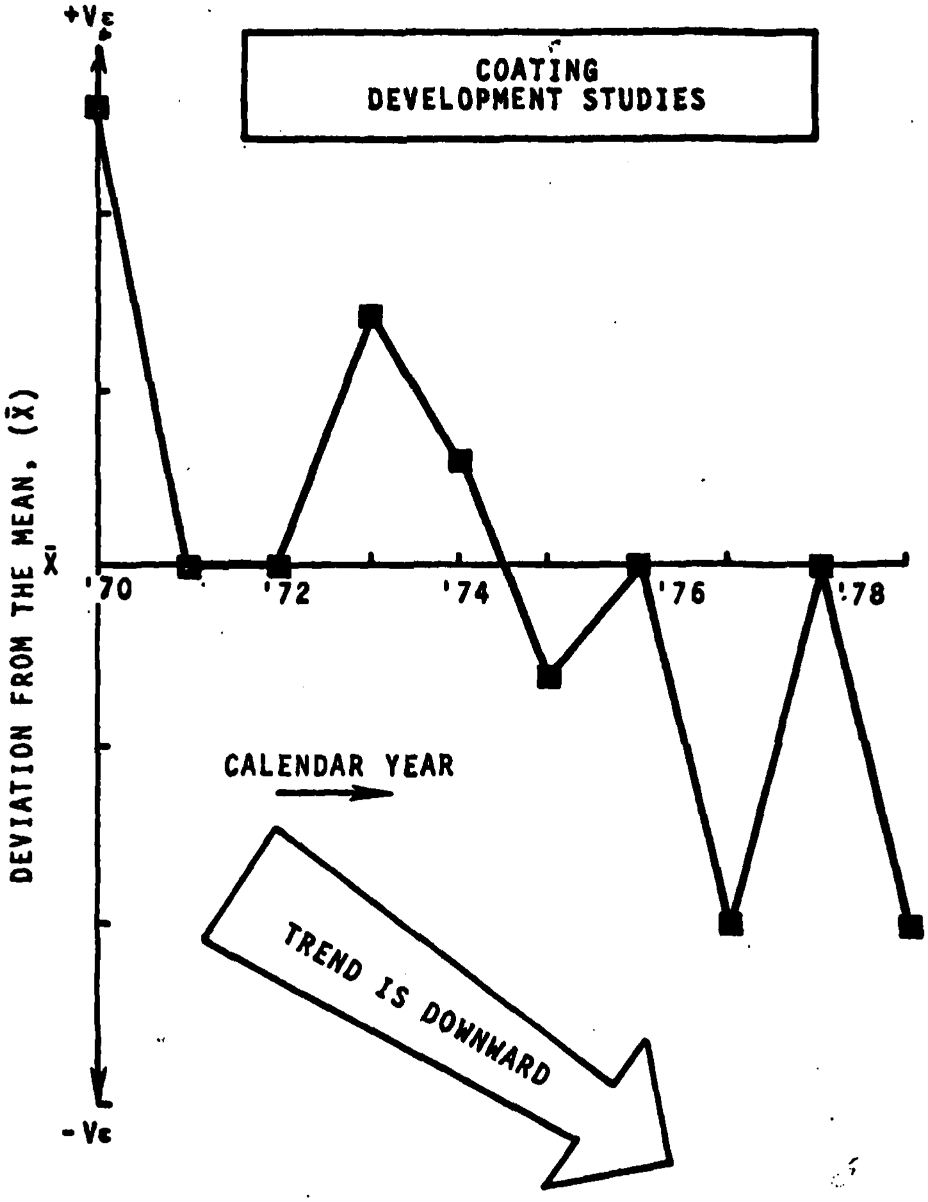


Figure 10 - Research Funding Trend by the U.S. Military for Coating Development Studies on Columbium.

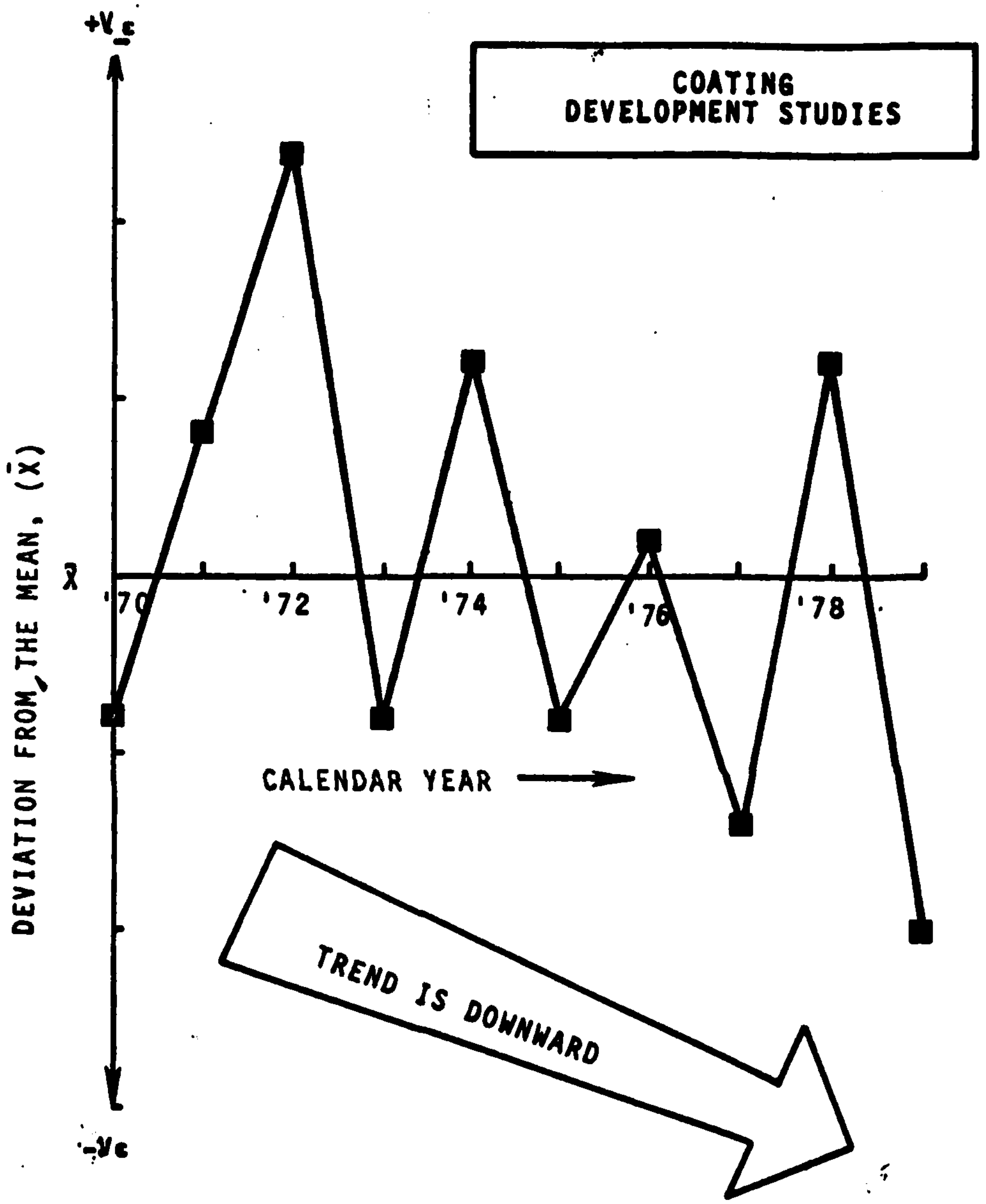


Figure 11 - Research Funding Trend by the U.S. Military for Coating Development Studies on Molybdenum.

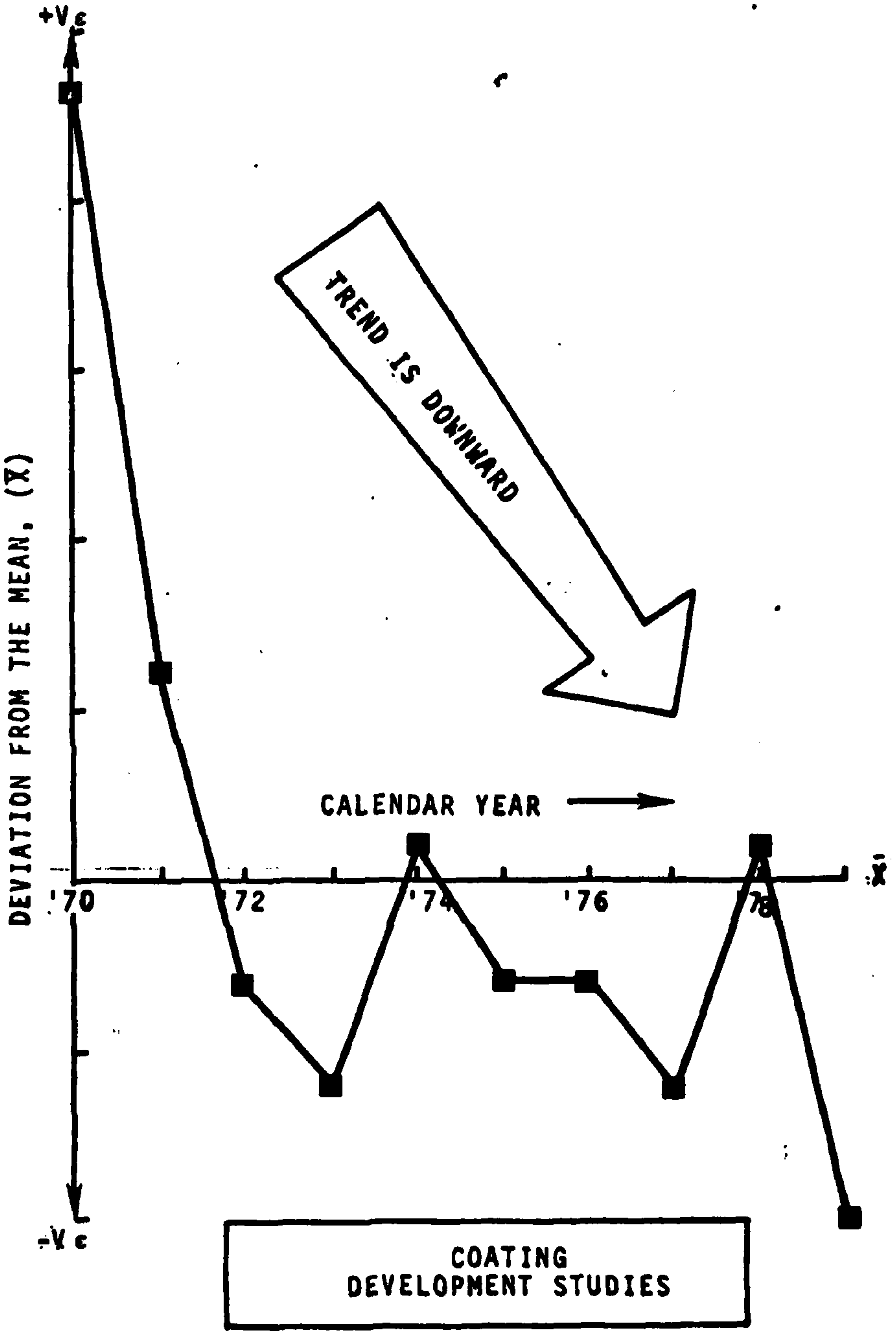


Figure 12 - Research Funding Trend by the U.S. Military for Coating Development Studies on Tantalum.

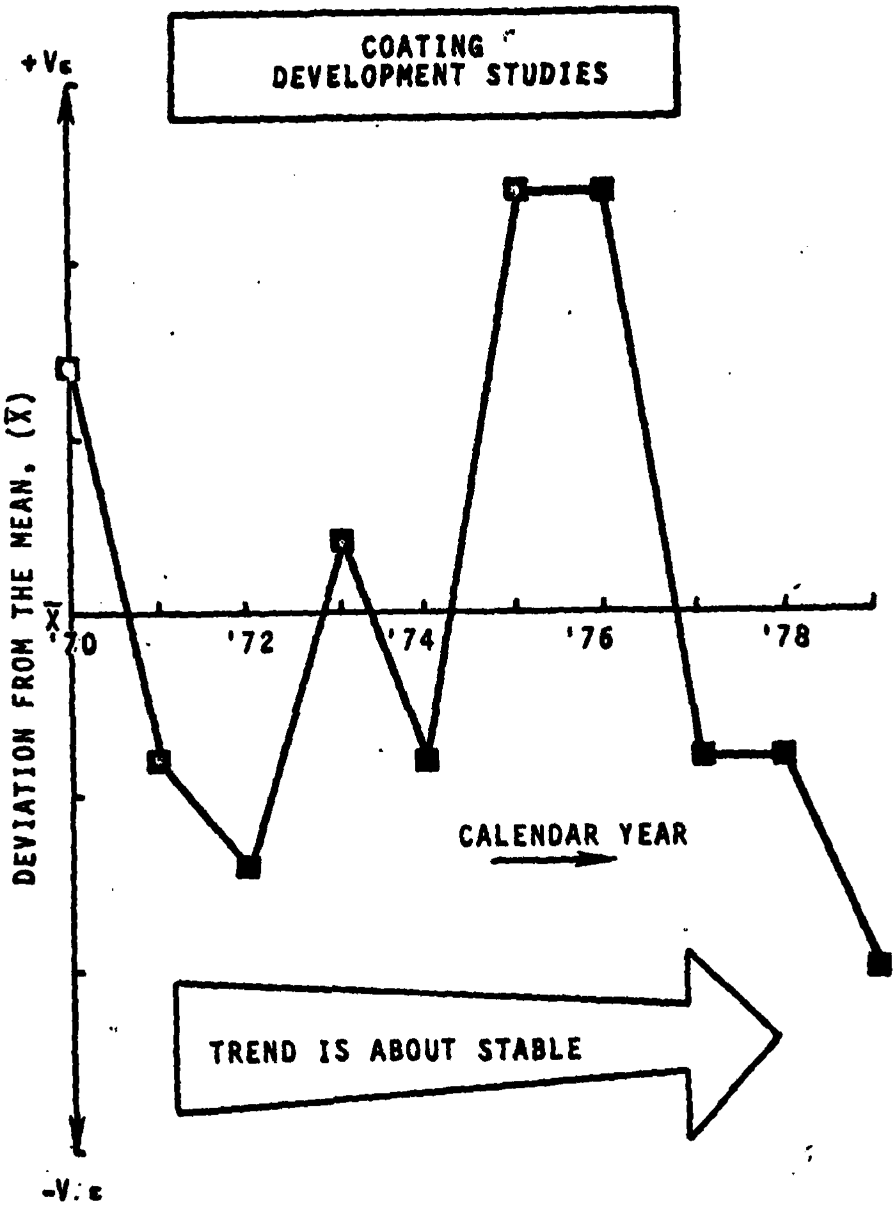


Figure 13 - Research Funding Trend by the U.S. Military for Coating Development Studies on Tungsten.

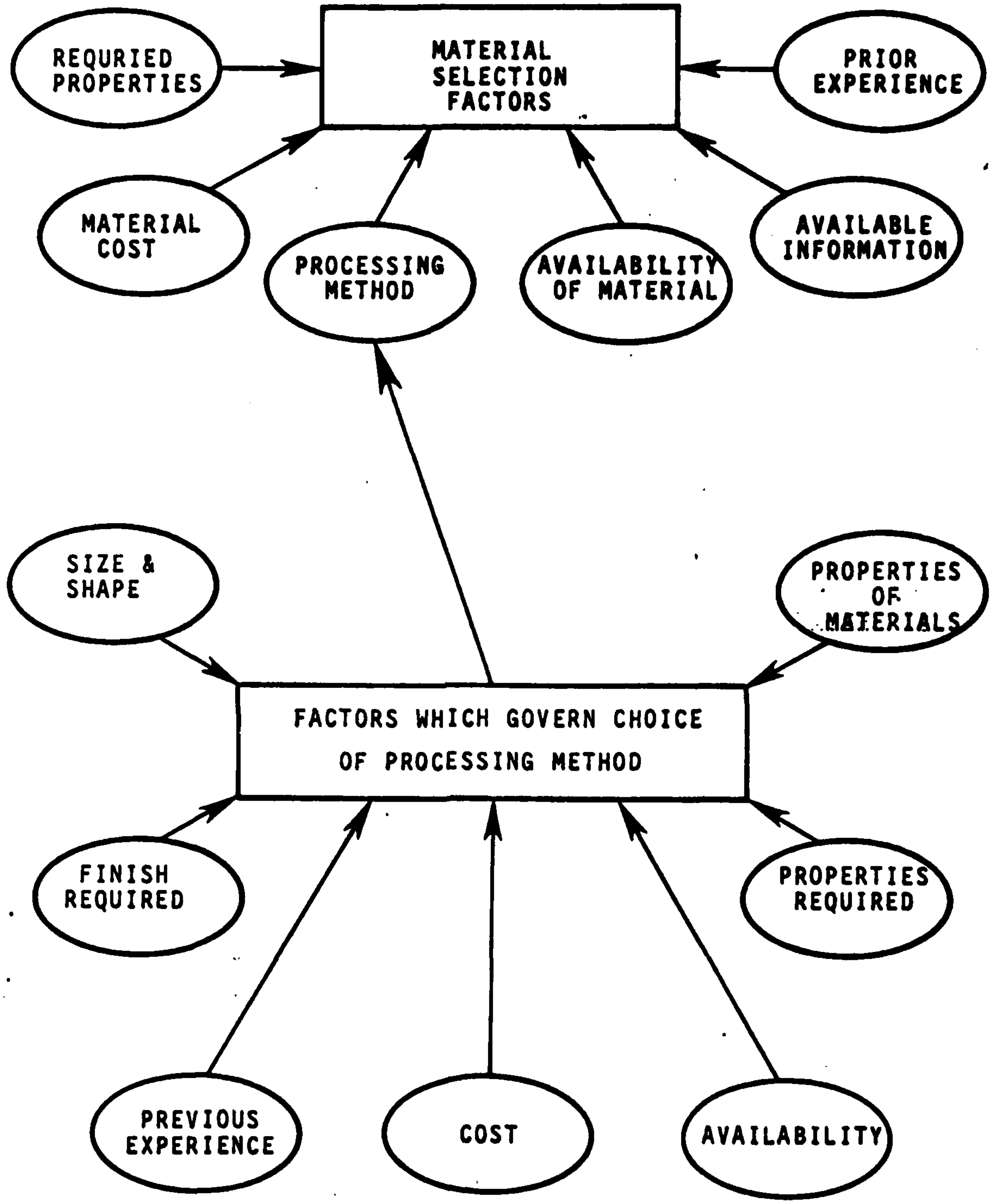


Figure 14 - Basic Parameters of Metallurgical Design.

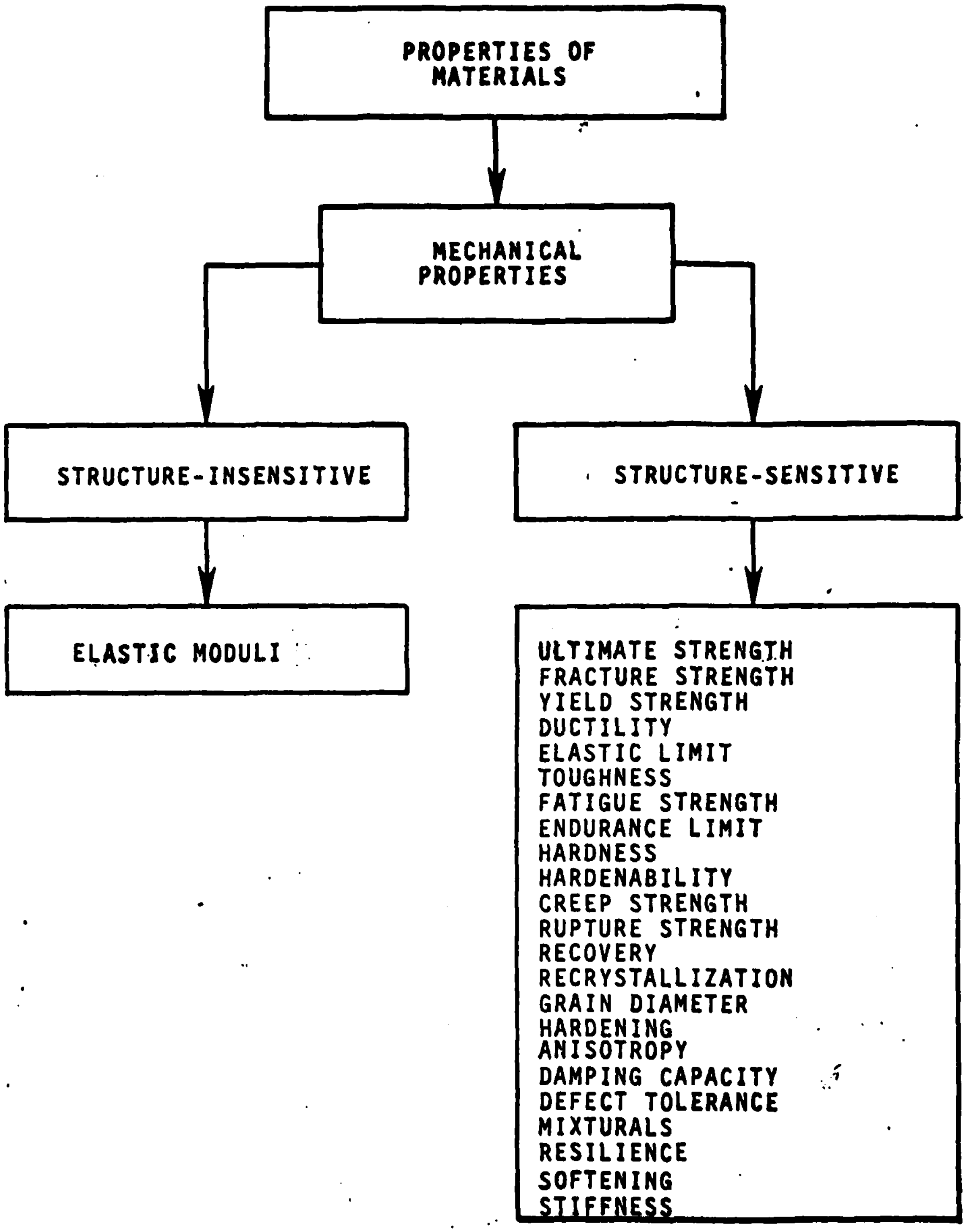


Figure 15a - Basic Components that influence Metallurgical Design Improvements, Continued.

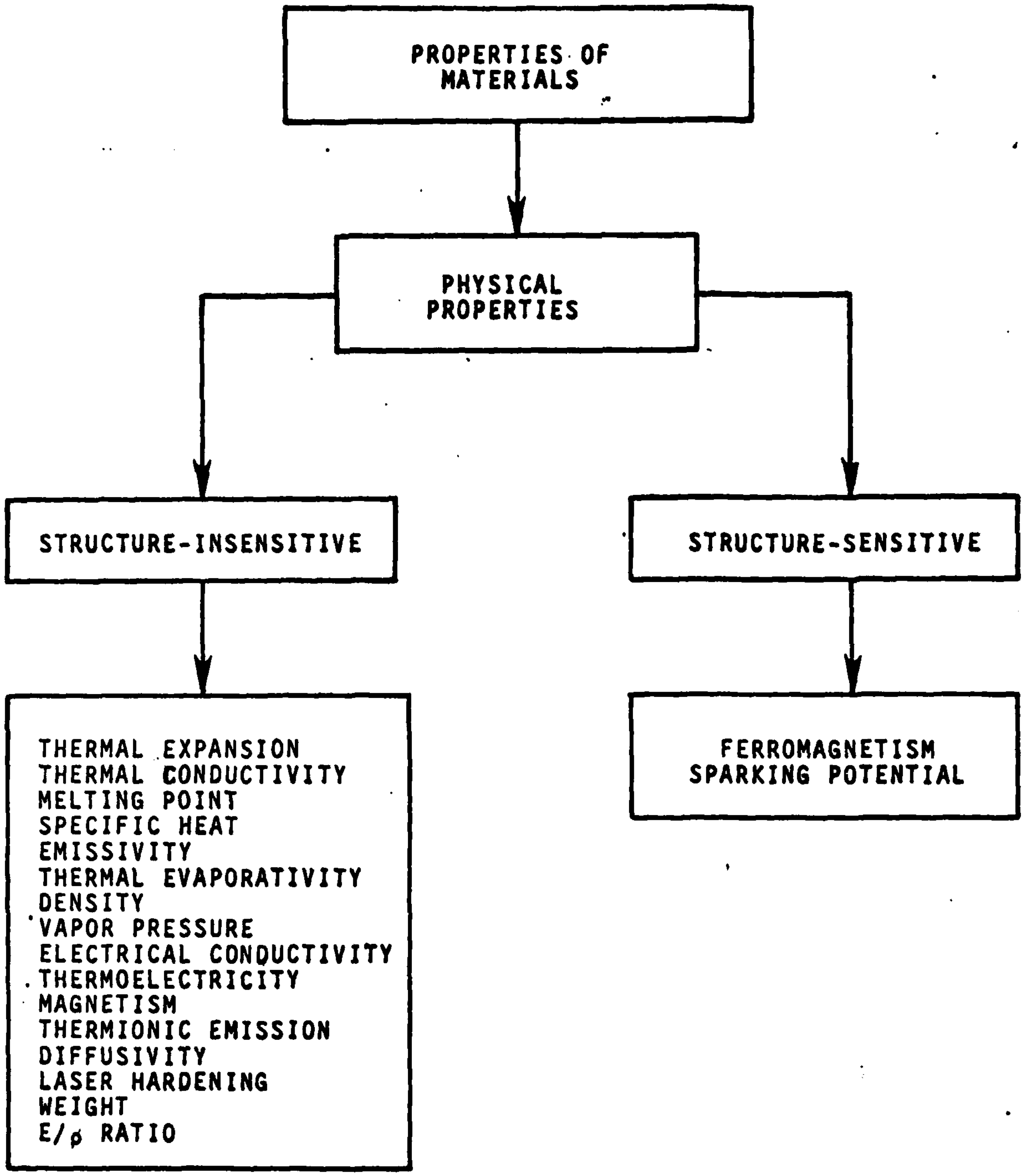


Figure 15b - Basic Components that Influence Metallurgical Design Improvements, Continued.

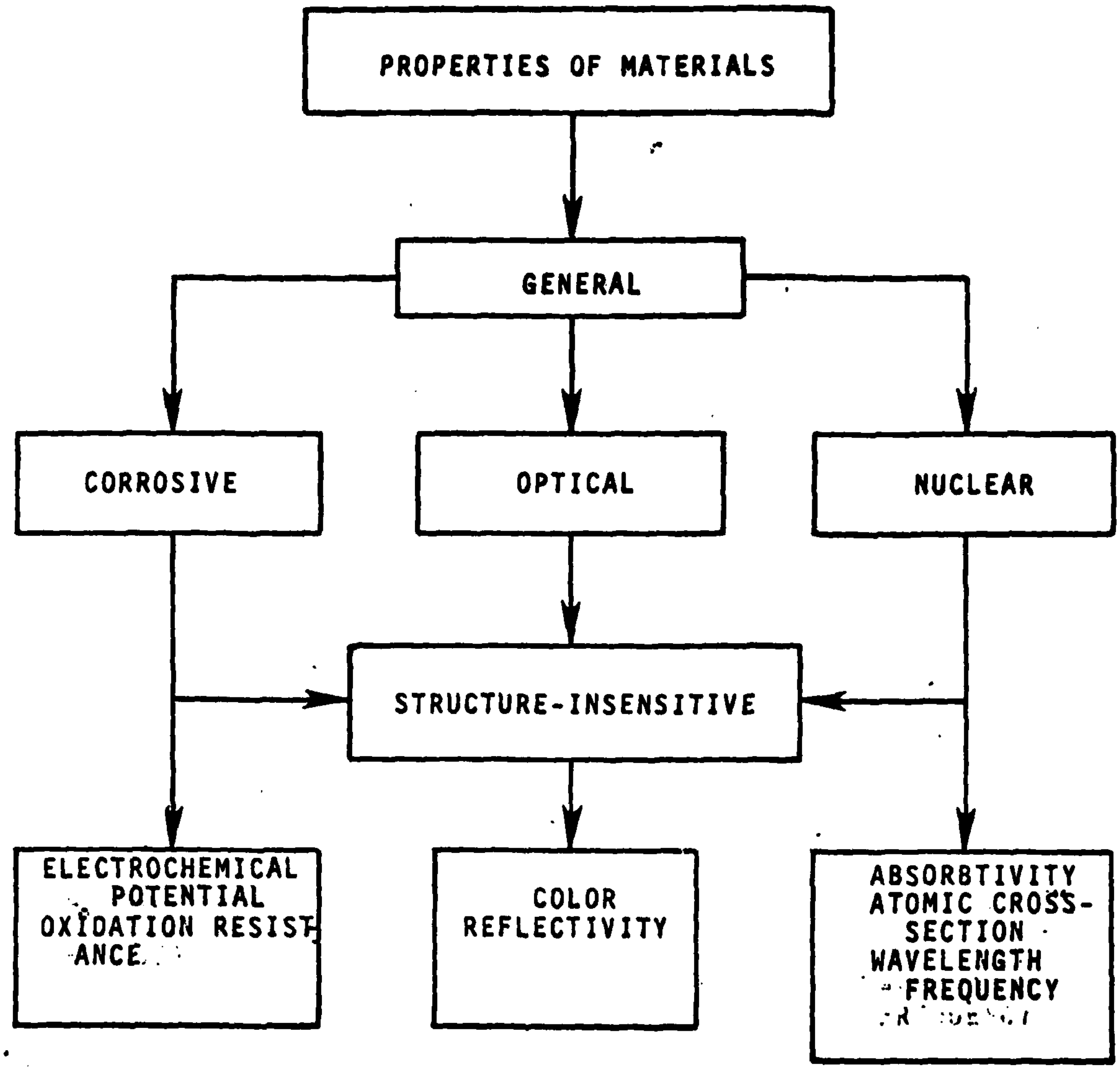


Figure 15c - Basic Components that Influence Metallurgical Design Improvements, Continued.

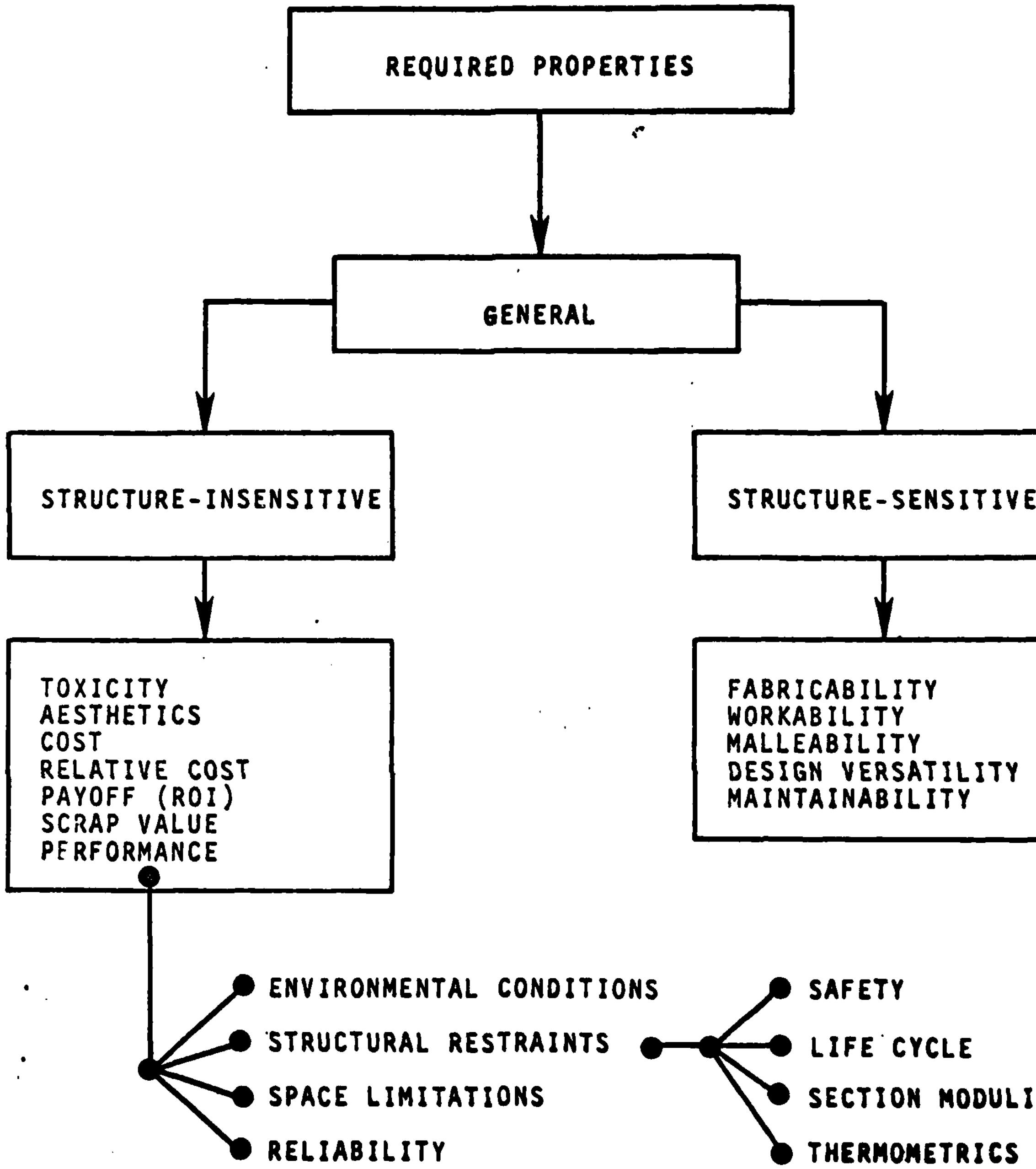


Figure 16 - Additional Factors that Influence Metallurgical Design Improvements.

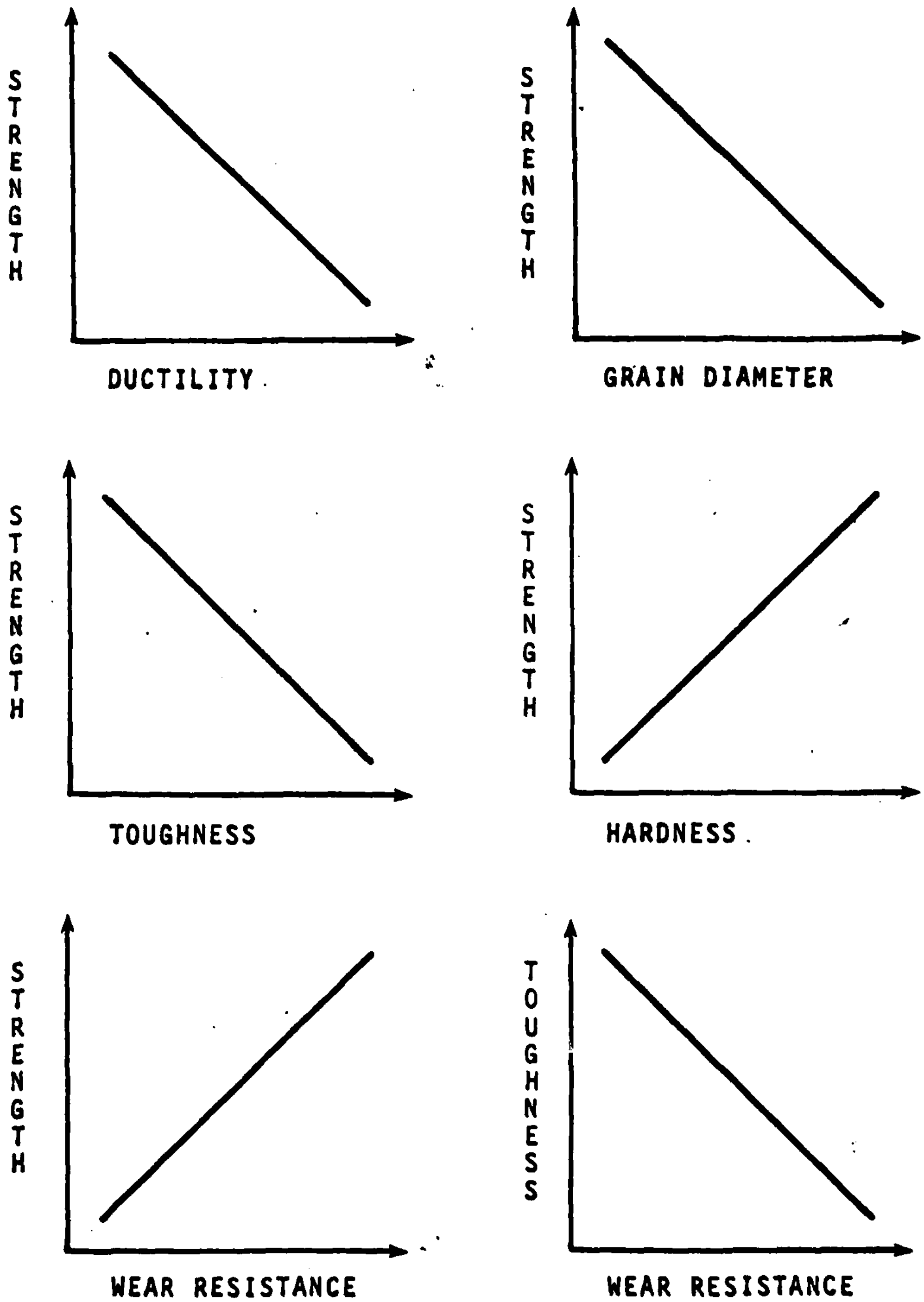


Figure 17a - General Design Trends for Most Single-Phase Alloys.

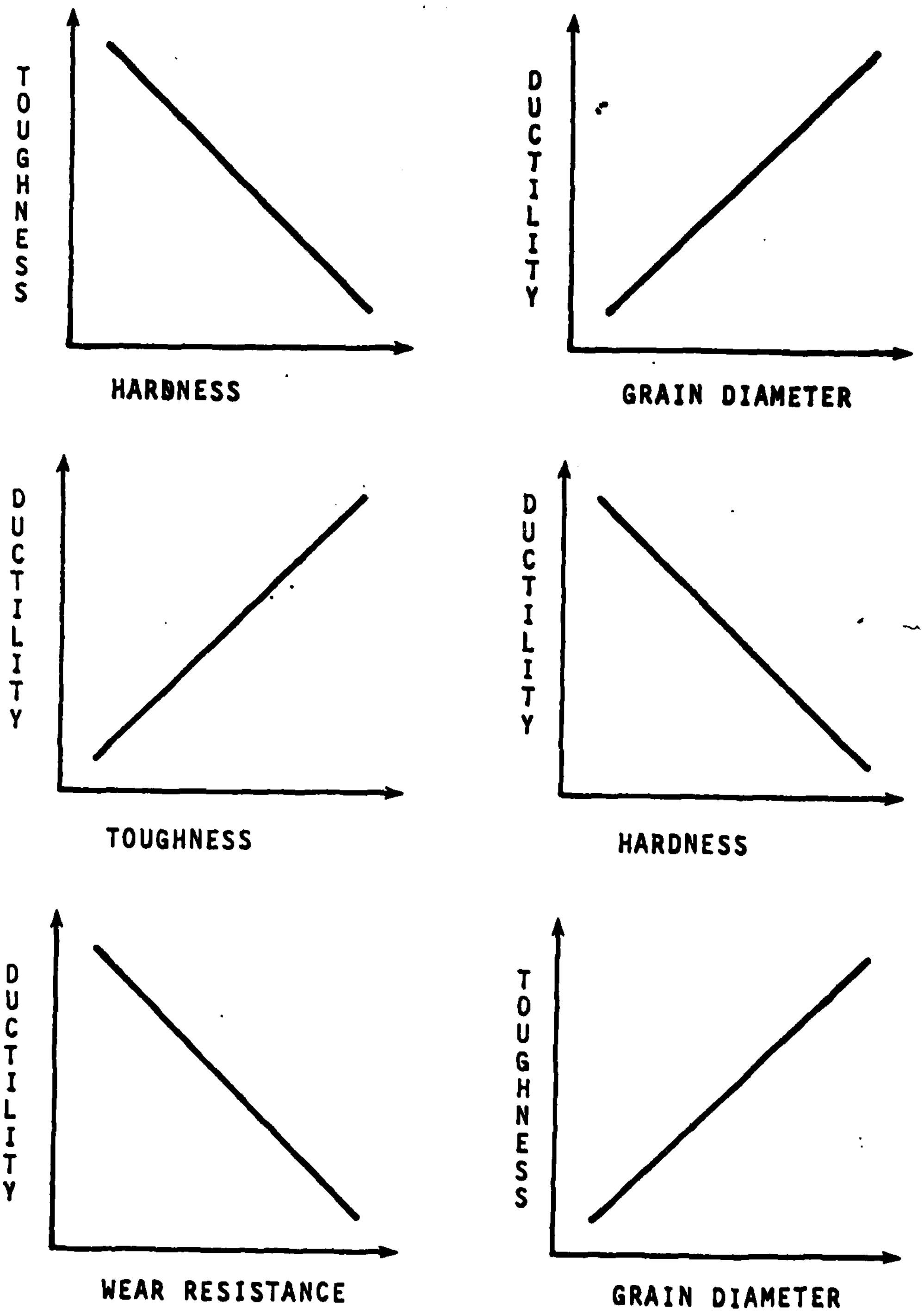


Figure 17b - General Design Trends for Most Single-Phase Alloys, Cont'd.

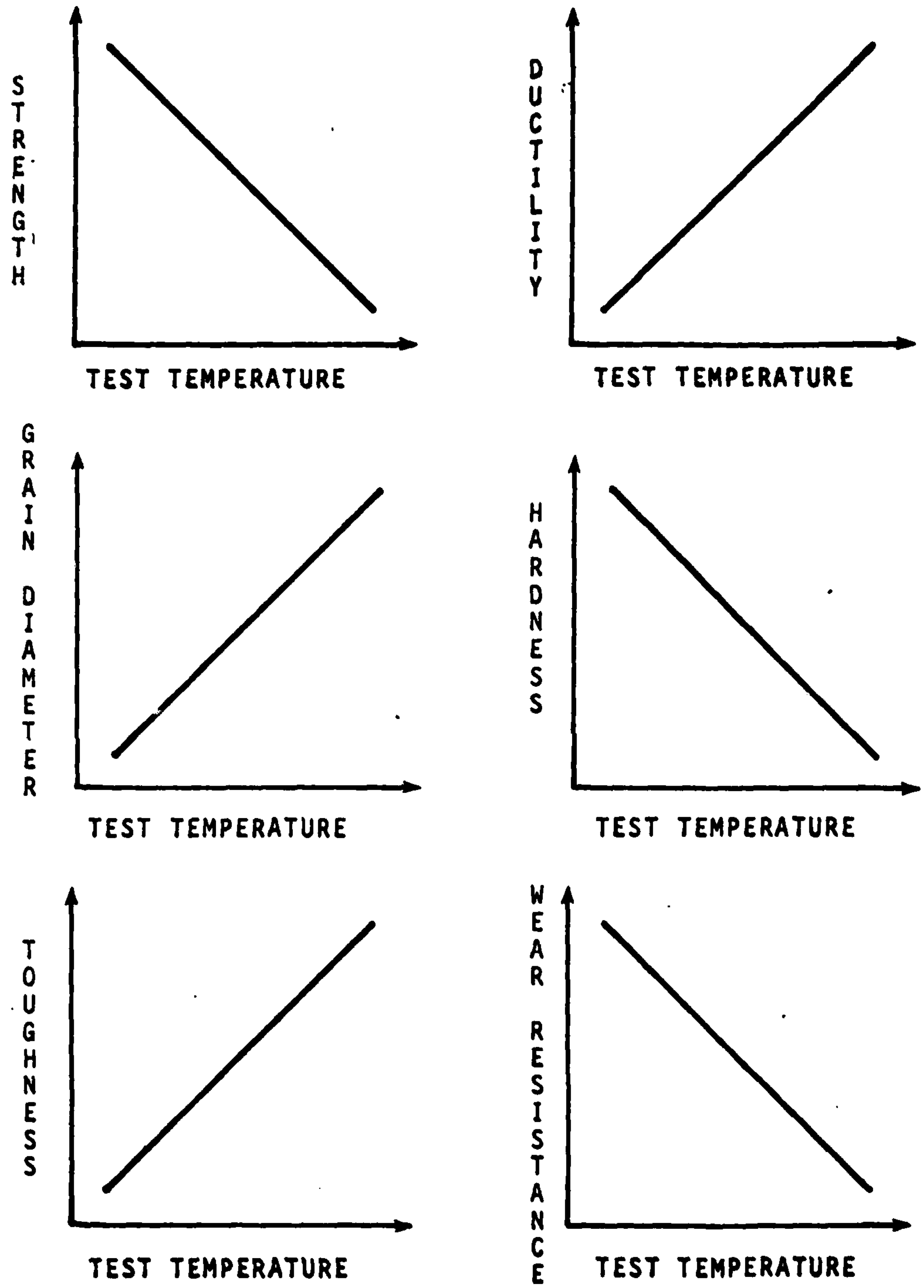
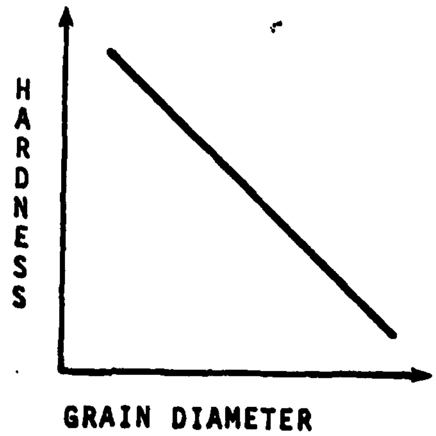


Figure 17c - General Design Trends for Most Single-Phase Alloys, Cont'd.



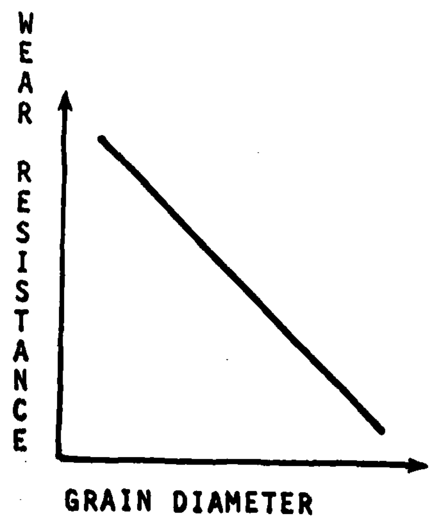


Figure 17d - General Design Trends for Most Single-Phase Alloys, Cont'd.

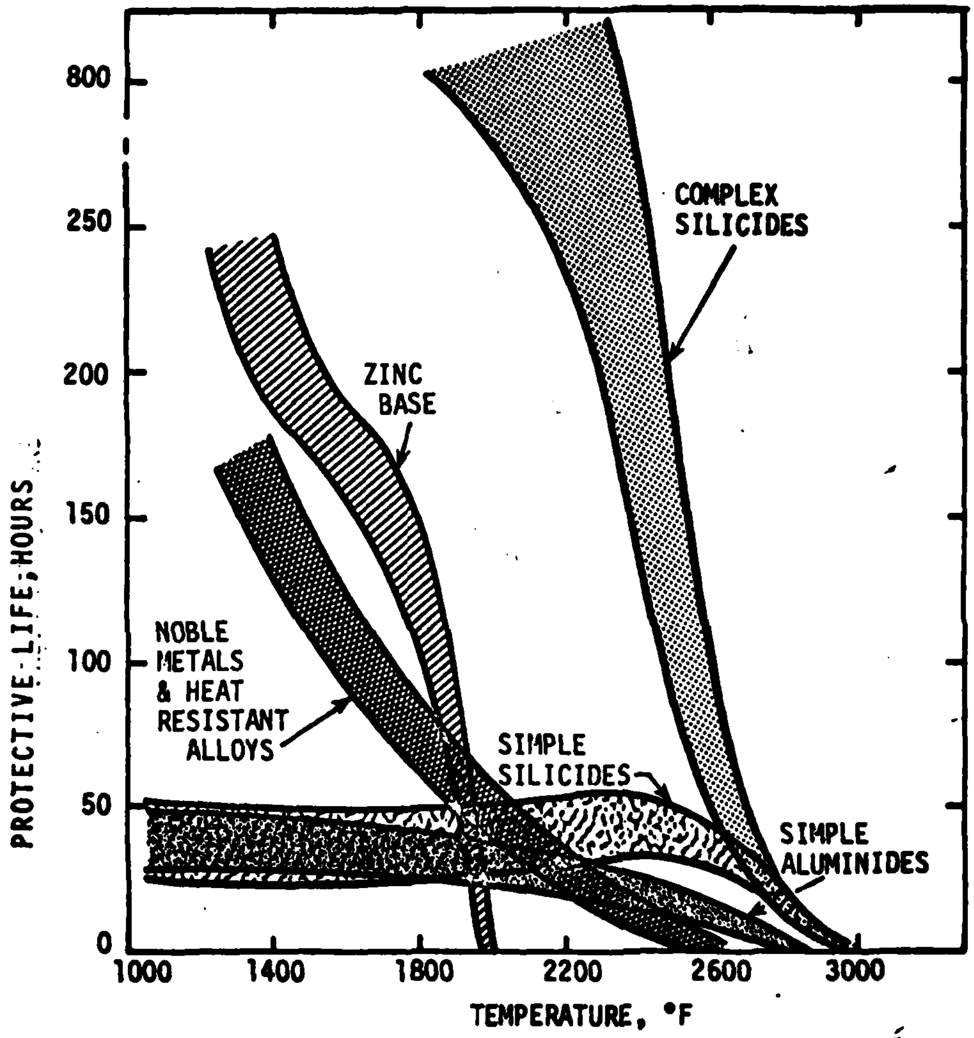


Figure 18 - Cyclic Oxidation Behavior of Different Coatings on Columbium-base Alloys (Taken from Reference 2).

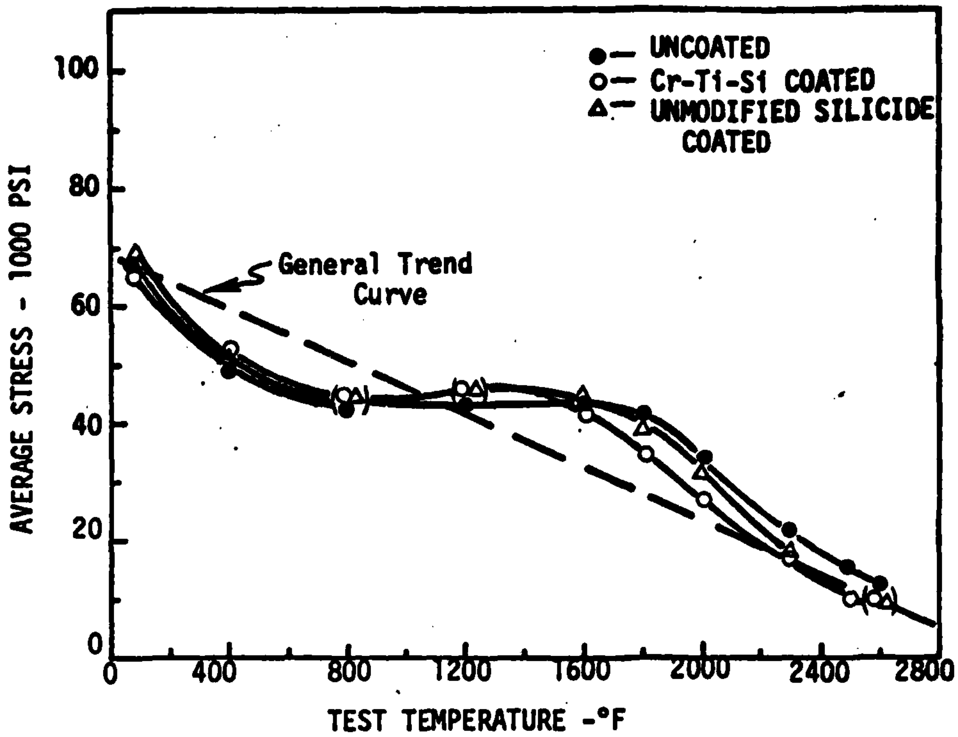


Figure 19 - Yield Strength Variations for Coated and Uncoated Columbium Alloy Sheet (Taken from Reference 2).

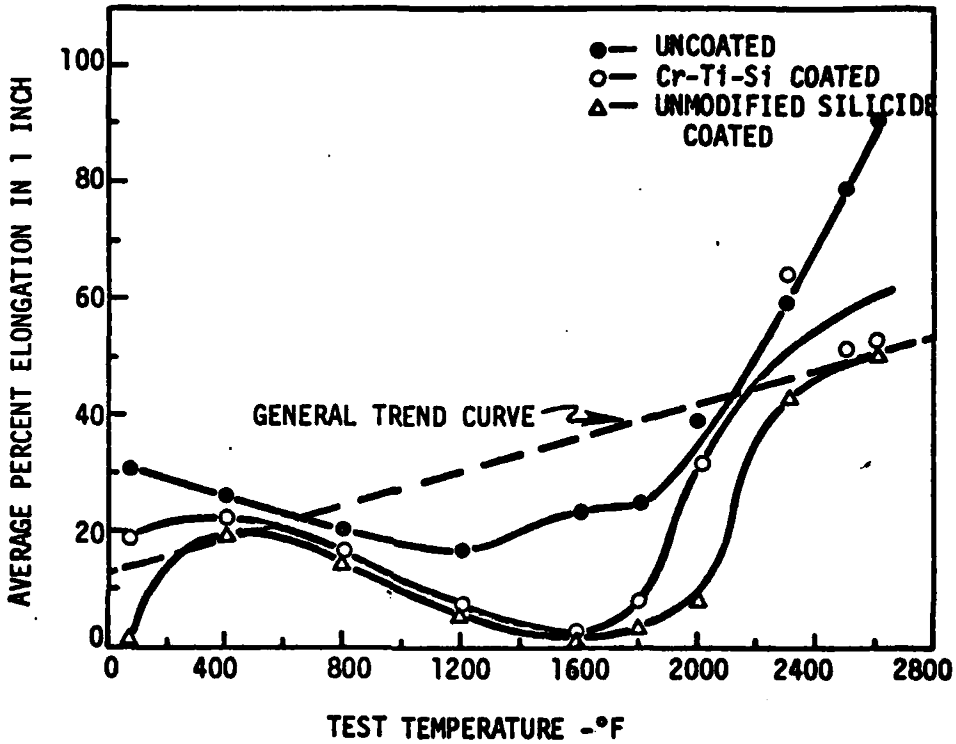
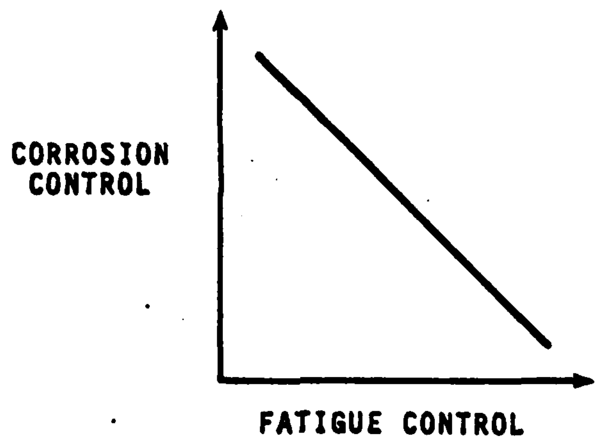


Figure 20 - Tensile Ductility Variations for Coated and Uncoated Columbium Alloy Sheet (Taken from Reference 2).



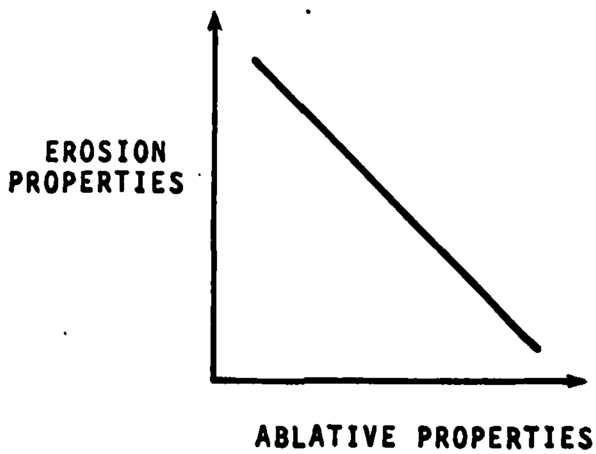


Figure 21 - Important Design Principles for Coatings.

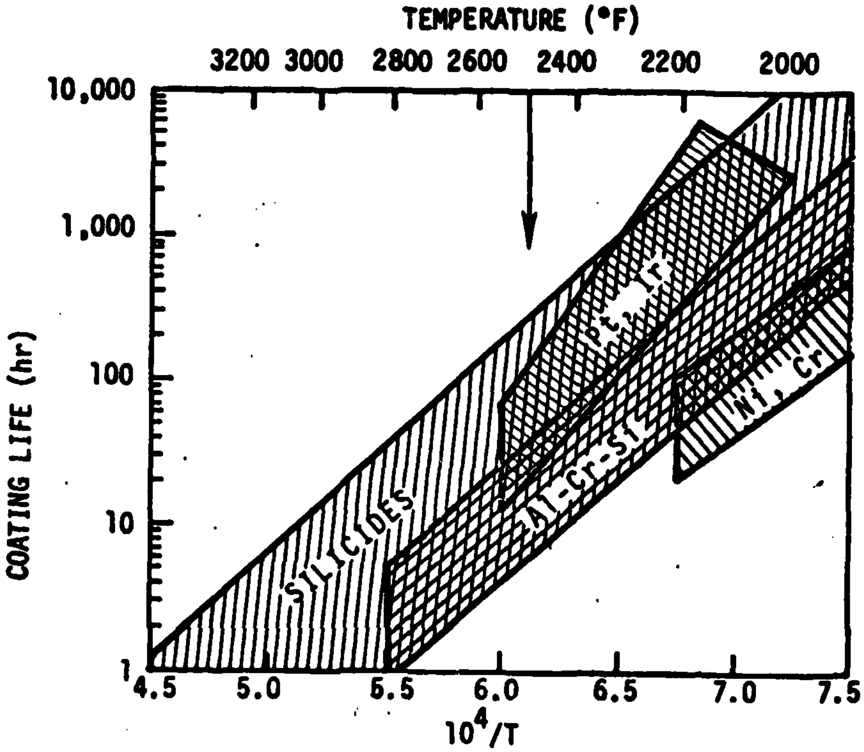


Figure 22 - Regions of Acceptable Performance for Coatings on Molybdenum in Air at Atmospheric Pressure (Taken from Reference 2).

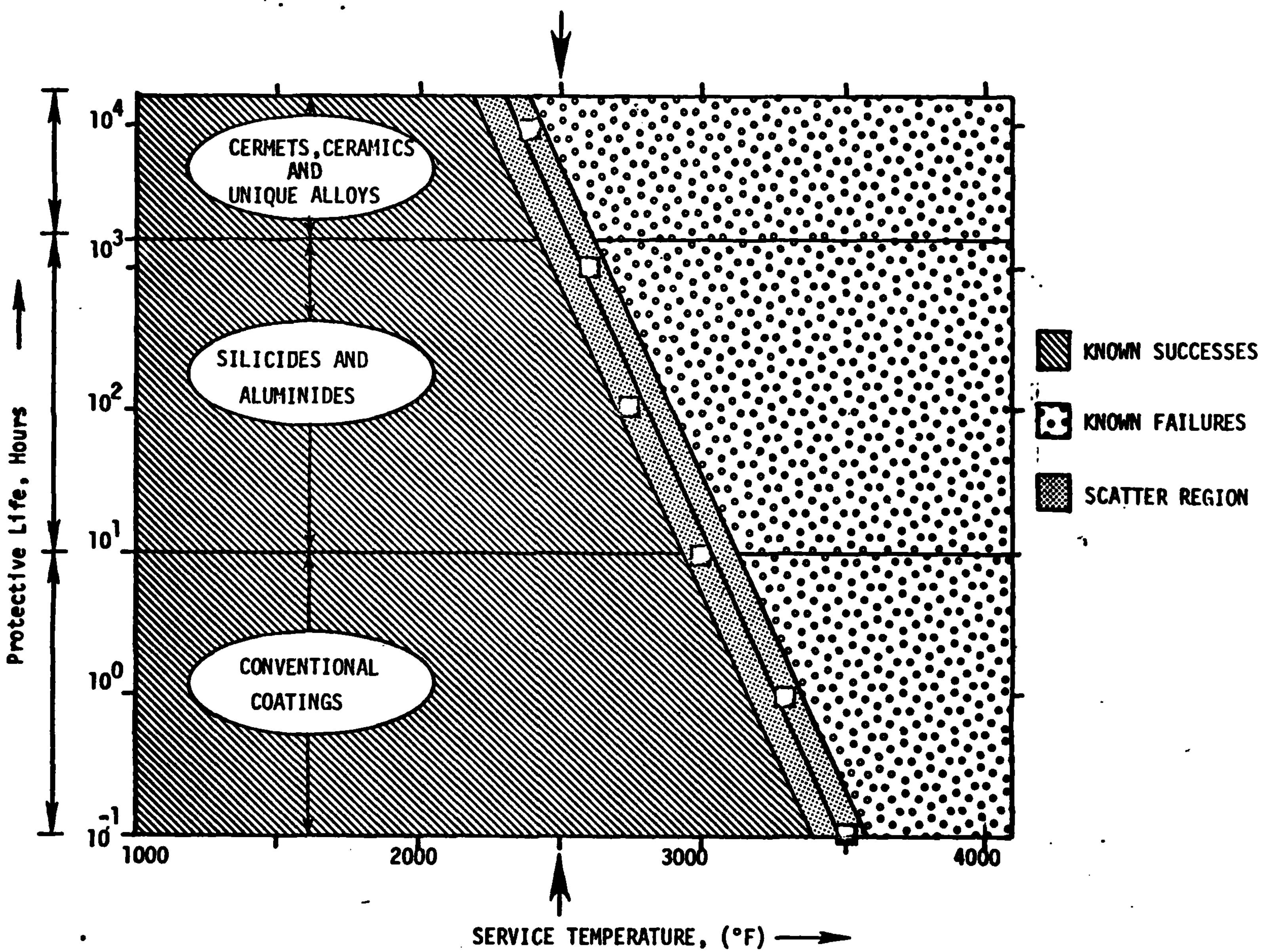


Figure 23 - Design Requirements and General Performance for thin Coatings on Cb, Mo, Ta and W (Taken from Reference 2).

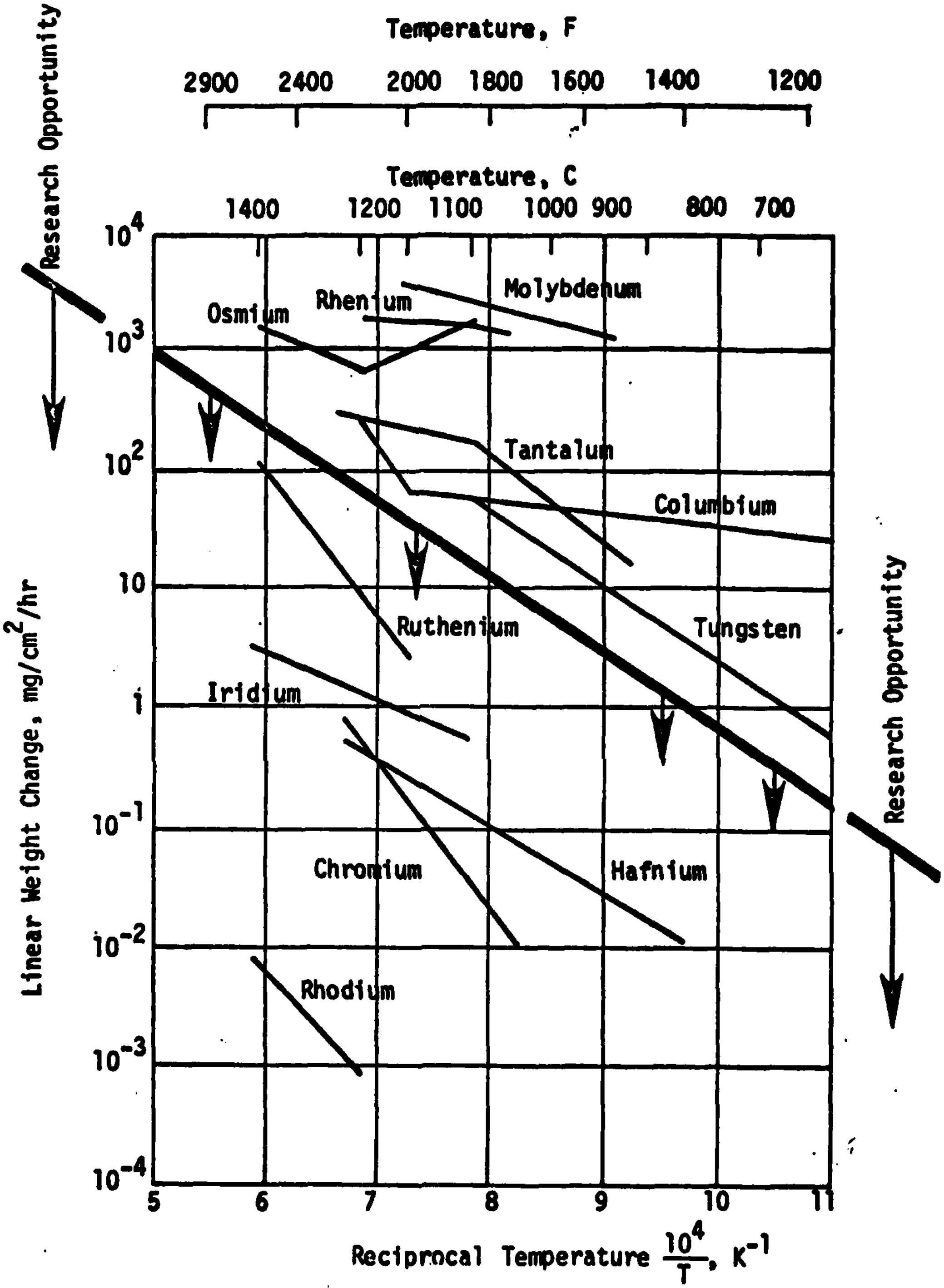


Figure 24 - The Oxidation-in-Air Behavior of the Refractory Metals (Taken from Reference 10).

TABLE I. ALLOY DEVELOPMENT NEEDS FOR Cb-X, Mo-X, Ta-X AND W-X SYSTEMS

SOLUTE ELEMENT FOR ALLOY SYSTEM	SOLVENT ELEMENT			
	Cb	Mo	Ta	W
Ag	●	---	●	---
As	---	●	●	---
Au	●	---	●	●
Ba	●	●	●	●
Bi	●	●	●	---
Ca	●	●	●	---
Cd	●	●	●	●
Ce	---	●	●	●
Cs	---	●	---	---
Gd	---	---	---	●
Hg	●	---	●	---
In	●	●	●	●
K	●	●	●	●
La	---	●	●	●
Li	●	●	●	●
Mg	●	---	●	---
Na	●	●	●	●
Pb	●	---	●	---
Pd	---	---	●	---
Sb	---	●	●	●
Se	---	---	---	●
Sn	---	●	---	●
Sr	●	---	●	---
Te	●	●	●	---
Y	●	●	●	●
Zn	●	---	●	●
$\sum = 26$	17	16	22	15

Note: (●) Means that Controversy Exists.

(---) Means that Controversy Does not Exist.

TABLE II. IMPORTANT TERNARY ALLOY SYSTEMS OF Cb-, Mo-, Ta- OR W- BASE

TERNARY ALLOY BASE ELEMENT	ALLOY DEVELOPMENT STATUS REPORT[1]
Columbium[2]	Limited Mainly to Commercial Alloys/Mixtures
Tantalum[2]	Ta-W-Cb, Ta-W-V, Ta-W-Mo, Ta-W-Cr, Ta-W-Re, Ta-W-Os, Ta-Cb-V, Ta-Cb-Mo, Ta-Cb-Cr, Ta-Cb-Re, Ta-Cb-Os, Ta-V-Mo, Ta-V-Cr, Ta-V-Re, Ta-V-Os, Ta-Mo-Cr, Ta-Mo-Re, Ta-Mo-Os, Ta-Cr-Re, Ta-Cr-Os, Ta-Re-Os
Tungsten[2]	W-Ta-Re, W-Ta-Zr, W-Cb-V, W-Cb-Mo, W-Cb-Cr, W-Cb-Re, W-Cb-Os, W-V-Mo, W-V-Cr, W-V-Re, W-V-Os, W-Mo-Cr, W-Mo-Re, W-Mo-Os, W-Cr-Re, W-Cr-Os, W-Re-Os
Molybdenum[2]	Mo-W-Re, Mo-W-C, Mo-Fe-C, Mo-Si-C, Mo-Ni-Fe, Mo-Co-Fe, Mo-Re-Hf, Mo-Ni-Co, Mo-Ni-Cr, Mo-Cr-Fe, Mo-Cr-Ti, Mo-Mn-Ti, Mo-Cr-Co, Mo-Ch-Ta, Mo-Cb-W, Mo-Ta-W

Notes: (1) Based on the findings of this Computer Aided Literature Search.

(2) Of the 54 Ternary Systems discovered, the distribution was in this Order: Ta(21), W(17), Mo(16) and Cb(0).

TABLE III. SURVEY OF BASIC RESEARCH (6.1) FUNDING ACTIVITIES ON COATING AND ALLOY DEVELOPMENT STUDIES FOR Cb, Mo, Ta AND W.

LIST OF GOVERNMENT FUNDING AGENCIES THAT WERE SURVEYED	BASIC RESEARCH ACTIVITIES Re.	
	ALLOYS	COATINGS
Defense Advanced Research Projects Agency, Washington, D.C. (Dr. Arden Bement)	RSR Powder (UTC) Cb (Teledyne-CAE)	None
Air Force Office of Scientific Research Washington, D.C. (Dr. Alan Rosenstein)	None	None
Office of Naval Research Washington, D.C. (Dr. Phil Clarken)	None	None
U.S. Bureau of Mines Washington, D.C. (Mr. Tom Jones)	None	None
Department of Energy Washington, D.C. (Dr. Louis Ianello)	None	None
Institute for Defense Analyses Arlington, Va (Dr. John Hove)	None	None
National Science Foundation Washington, D.C. (Dr. R. Arsenault)	None	None
National Aeronautics and Space Administration Cleveland, Ohio (Mr. John Freche)	Fiber Reinforced W Alloy (1@ TRW & 4 @ In-House)	None
Army Research Office Durham, NC (Dr. George Mayer)	Would Not Respond	Would Not Respond

COMPUTER

AIDED

LITERATURE

FINDINGS

READER'S GUIDE FOR COMPUTER-AIDED-LITERATURE FINDINGS (CALF)

Contents and Outline Scheme

1.0 Columbium

1.1 Alloy Development Studies on Columbium

1.1.1 Significant Early Contributions

A-1 Klopp, "Diffusion Rates and Solubilities of Interstitials in Refractory Metals", DMIC Memo 50, April 1960.

A-2 Seybolt, "Solid Solubility of Oxygen in Niobium", Jour of Metals, 774, June 1954.

A-3 Elliott, "Columbium-Oxygen System", Amer Soc of Metals, Preprint No. 143, 1959.

A-4 Brauer, "Nitrides of Niobium", Zeitschr. fuer Anorgan und Allgemeine Chemie, 270, 160 1952.

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A-6 Schonberg, "Some Features on the Nb-N System", Acta Chemica Scandinavica, 8, 208, 1954.

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A-8 Albrecht, "Niobium - Hydrogen", Jour of Electrochem Soc, 219, April 1958.

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A-24 Knapton, "The Nb-Ru System", See Ref. A-19.

A-25 Greenfield, "The Nb-Ru System", See Ref. A-21.

A-26 Buckle, "The Nb-Ta System", See Ref. A-17.

A-27 Williams, "The Tantalum-Columbium Alloy System", Trans Amer Soc of Metals, 50, 1081, 1958.

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A-58 Greenfield, "The Nb-Pd System", See Ref. A-21.

A-59 Greenfield, "The Nb-Pt System", See Ref. A-21.

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1.1.2 Recent Government Contributions

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B-4 UTC, "Investigation to Develop A High Strength Eutectic for Aircraft Engine Use", AD 887395, July 1971.

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R-32 NSWC, "Development of Laser Resistant Coatings", AD C0151642L, July 1978.

GLOSSARY FOR GOVERNMENT AUTHORS

Acronym	Definition	Typical Reference
AEDC	Arnold Engineering Development Center Arnold Air Force Station, Tennessee	K-17
AFAL	Air Force Armament Laboratory Eglin Air Force Base, Florida	F-6
AFAPL	Air Force Aero-Propulsion Laboratory Wright-Patterson Air Force Base, Ohio	B-24
AFFTD	Air Force Foreign Technology Division Wright-Patterson Air Force Base, Ohio	H-1
AFML	Air Force Materials Laboratory Wright-Patterson Air Force Base, Ohio	D-28
AFWL	Air Force Weapons Laboratory Kirtland Air Force Base, New Mexico	F-4
AFOSR	Air Force Office of Scientific Research Bolling Air Force Base, D.C.	M-20
AFRPL	Air Force Rocket Propulsion Laboratory Edwards Air Force Base, California	B-8
AMMRC	Army Materials and Mechanics Research Center Watertown, Massachusetts.	F-22
ARDC	Army Armament Research and Development Command Aberdeen Proving Ground, Maryland	O-27
ARFSTC	Army Foreign Service and Technology Center Charlottesville, Virginia	F-17
BCRA	British Ceramic Research Association Stroke-on-Trent, England	H-7
BI	Beckman Instruments, Inc. GIDEP Operations Corona, California	R-21
BMI	Battelle Memorial Institute Columbus, Ohio	D-12
CC	Chemetal Corporation Pacoima, California	R-20

CMU	Carnegie-Mellon University Pittsburgh, Pennsylvania	B-15
DARCOM	Army Materials and Mechanics Research Center Watertown, Massachusetts	B-28
DDC	Defense Documentation Center Alexandria, Virginia	M-2
DF	Deutsche Forschungs und Versuchsanstalt Fuer Luft- und Raumfahrt E.V. Munich, Germany	H-8
DL	Charles Stark Draper Laboratory, Inc. Cambridge, Massachusetts	F-18
DMRD	Directorate of Materials Research and Development London, England	H-5
DOA	Department of Army Thomas J. Rodman Laboratory Rock Island Arsenal, Illinois	F-11
DoD	Department of Defense Washington, D.C.	F-5
DRDAR	Army Armament Research and Development Command Aberdeen Proving Ground, Maryland	F-25
DU	Drexel University Philadelphia, Pennsylvania	F-16
FMC	Food Machinery Company, Inc. Santa Clara, California	F-1
FMSAE	Fleet Missile Systems Analysis and Evaluation Group Corona, California	M-14
GAE	Grumman Aircraft Engineering Corporation Bethpage, New York	D-3
GE	General Electric Company Burlington, Vermont	F-3
GIT	Georgia Institute of Technology Atlanta, Georgia	H-18

Glossary, Cont'd

HI	Honeywell, Incorporated Minneapolis, Minnesota	H-17
HRL	Hughes Research Laboratories Malibu, California	B-16
IDA	Institute for Defense Analyses Arlington, Virginia	B-1
IITRI	Illinois Institute of Technology Research Institute Chicago, Illinois	R-12
MDA	McDonnell Douglas Astronautics St. Louis, Missouri	D-1
ML	Manlabs, Incorporated Cambridge, Massachusetts	K-5
MMC	Martin-Marietta Corporation Orlando, Florida	B-3
NADC	Naval Air Development Center Warminster, Pennsylvania	H-3
NASC	Naval Air Systems Command Pennsacola, Florida	H-32
NBS	National Bureau of Standards Gaithersburg, Maryland	K-4
NRL	Naval Research Laboratory Washington, D.C.	F-12
NSA	National Security Agency Fort Meade, Maryland	D-13
NSEC	Naval Ship Engineering Center Hyattsville, Maryland	F-14
NSRD	Naval Ship Research and Development Center Annapolis, Maryland	O-15
NSWC	Naval Surface Weapons Center White Oak-Silver Spring, Maryland	H-33
ONR	Office of Naval Research Arlington, Virginia	R-3

PA	Picatinny Arsenal Dover, New Jersey	H-12
PE	Perkin-Elmer Corporation Norwalk, Connecticut	H-22
RADCOM	Renet Weapons Laboratory Dover, New Jersey	F-27
RAE	Royal Aircraft Establishment Farnsborough, England	H-10
RI	Rockwell International Los Angeles, California	H-2
SAI	Sanders Associates, Incorporated Nashua, New Hampshire	D-14
SAMSO	Space and Missile Systems Organization El Segundo, California	F-23
SEP	Sylvania Electric Products, Incorporated Hicksville, New York	D-11
SOL	Solar Division International Harvester, Inc. San Diego, California	D-25
SPS	Standard Pressed Steel Company Jenkintown, Pennsylvania	K-3
SWRI	Southwest Research Institute San Antonio, Texas	R-25
TI	Texas Instruments, Inc. Dallas, Texas	H-9
TRW	Thompson-Ramo-Woolridge, Inc. Cleveland, Ohio	D-27
UM	University of Minnesota Minneapolis, Minnesota	H-4
UTC	United Technologies Corporation Hartford, Connecticut	F-24
WA	Watervliet Arsenal Watervliet, New York	H-27

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FINAL REPORT

GAS PHASE REACTIONS OF SOME HYDRATED IONS

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GAS PHASE REACTIONS OF SOME HYDRATED IONS

by

Michael J. Henchman

ABSTRACT

As major positive ion constituents of the stratosphere and mesosphere, the hydrated oxonium ions, $H_3O^+(H_2O)_n$, are of considerable interest. These ions together with the complementary negative ions $OH^-(H_2O)_n$ are principal ionic species in aqueous solution chemistry. Using isotopically labelled reactants and a double mass spectrometer system, we have begun a systematic study of the reactions of these species with neutral water molecules, for relative energies ranging from a few tenths of an electron volt to a few electron volts. The present report describes the results obtained for the simplest members of these series: H_3O^+ and OH^-. At the highest energies studied, the primary reaction pathway involved the discrete transfer of a proton; as the energy is reduced there is an increasing relative contribution from rearrangement processes; and, for the positive ion reaction, there is independent evidence that there is complete scrambling of the hydrogens within the reaction intermediate at thermal energies. Extrapolation of the present results suggests that the same holds for the negative ion reaction at thermal energies. For both positive and negative ion reactions, the ion-molecule binding energy provides sufficient excitation energy within the intermediate to drive the rearrangement; the extent of the rearrangement is determined by the lifetime of the intermediate; and this lifetime is in turn determined by the relative energy. Such studies yield insight into the dynamic properties of excited water clusters.

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I. INTRODUCTION:

Ionospheric electron densities, and hence the properties of the ionosphere as a medium for radio wave propagation, are controlled by a complex set of reactions involving electrons, ions and neutral species. Computer models used for predicting the effects of natural and nuclear perturbations upon the ionosphere require as inputs the rate constants and cross sections, together with their temperature and energy dependences, of literally hundreds of reactions. Rocket-borne mass-spectrometer measurements of the ionic species have shown that hydrated positive and negative ions are dominant species in the lower ionosphere. The reactions forming and destroying these hydrated ions have therefore recently become of considerable interest in aeronomy.[1] In addition to their occurrence in the ionosphere, these same species are found in aqueous solutions and in flames and plasmas: thus the elucidation of their chemical reactions has a wide applicability to several different situations.

A program of research in atmospheric ion chemistry has existed for several years at the Air Force Geophysics Laboratory and several graduate students from Brandeis University have taken advantage of the double mass spectrometer systems at AFGL to carry out portions of their research programs. The existence of the USAF - SCEEE Summer Faculty Research Program provided an opportunity for this long standing informal collaboration to be continued in a closer and mutually more beneficial way.

The advantages to be gained from this collaboration have recently received added emphasis from the convergence of our interests to focus on the chemistry of hydrated ions. Previous studies at AFGL had concentrated on an extensive series of switching reactions, of collison-induced dissociations and of ion photochemistry: one consequence of this program is an accumulation of expertise in the production of both hydrated positive and negative ions. This by itself would have provided sufficient inducement for my participation in the program.

The development of my own interest in the chemistry of hydrated ions has followed a somewhat different direction, evolving originally from the desire to use the detailed results available for the gas phase to seek understanding of the processes occurring in aqueous solution. This formed a major focus for a review article, written in 1972,[2] and provided the motivation for a collaborative project with Drs. Smith and Adams at the Department of Space Research at Birmingham University, England, in the summer of 1978. There we were able to use the Selected Ion Flow Tube (SIFT) technique for the first time to study the reactions of hydrated ions at 300 K, specifically those of $H_3O^+(H_2O)_{0,1,2}$ with both water and ammonia.[3] The results not only yielded new insights into the dynamic properties of excited ion clusters but allowed the formulation of a general model for such systems. The opportunities at AFGL allowed the development of this work, with particular reference to its extension to systems of negative ions and to the effect of increasing energy.

II. OBJECTIVES

The principal objectives of the long-range program were to explore how the solvation of ions affects the chemical reactivity of those ions, as a function of the number and identity of the solvent molecules. Because of their importance in the middle atmosphere and in aqueous solution chemistry, hydrated ions were selected and their particular reaction chosen was the proton-transfer reaction. Two specific questions were of interest. Is the effect of the ion solvation the same whether the ion be a positive ion or a negative ion? How does the effect of the ion solvation vary with the energy of the reacting species?

Thus the particular objectives of the summer program were to study the reactions $H_3O^+(H_2O)_n$ and $OH^-(H_2O)_n$ with water itself. Specifically the cross sections for these reactions would be measured as a function of relative translational energy, using isotopic labelling for identification.

These studies on the ion beam apparatus at AFGL were expected to complement the similar studies carried out during the summer of 1978 at the University of Birmingham using the SIFT technique. On the basis of these previous SIFT results at 300 K, a general model has been formulated for the proton-transfer reactions of solvated ions. It was one purpose of the present study to test the predictions of this model with respect to the charge state of the ion and the dependence on energy. Furthermore the SIFT studies on the system $H_3O^+(H_2O)_{0,1,2} + H_2O$ provide a data set to which the ion beam results must extrapolate in the limit of low energy.[3]

III. APPARATUS

The ion beam apparatus AFGL, used in this research, has been described.[4] It is a longitudinal tandem mass spectrometer, consisting of a small, magnetic-sector mass spectrometer (90 degree, 2.54 cm. radius of curvature), a thin collision chamber, and a quadrupole mass analyzer. A mass analyzed beam of reactant ions, produced in the sector mass spectrometer, is accelerated or decelerated to the desired energy and enters the collision chamber, where reactions may occur in collision with the reactant gas, held at known pressure. Ions issuing from the collision chamber are accelerated and focused into the quadrupole mass analyzer and are then counted with appropriate pulse counting equipment.

Useful reactant ion beams at particle energies as low as 0.5 eV can be obtained routinely. The principal source of error in measuring cross sections with this apparatus is the uncertainty in the collection efficiency of product ions. Because this efficiency is generally less than that for reactant ions, measured cross sections should be regarded as lower limits to the true cross sections and may, in the most unfavorable cases, be low by a factor of about 2.5.

Other limitations in the double mass spectrometer system arise from the spread in ion energy of the reactant ion beam (about 0.5 eV full width at half maximum in the lowest energy range used in the present study), the uncertainty in the most probable ion energy (about 0.3 eV), and the limited resolution of the sector mass spectrometer. Under certain conditions isotopically pure beams of a known mass-to-charge ration cannot be prepared and appropriate "background" corrections must be made to the data in such cases.

The ion source is operated at high pressure (approximately 10 microns) and useful beams of H_3O^+, $H_3O^+(H_2O)$, OH^- and $OH^-(H_2O)$ are readily prepared. It is also possible that useful beams of the dihydrate could be obtained although this was not attempted in the present study.

IV. CONTROL EXPERIMENTS

An extensive study had been undertaken previously on the AFGL ion beam machine of the switching reaction $OH^-(H_2O) + CO_2 = HCO_3^- + H_2O$ and this excitation function (cross section as a function of relative translation energy) was reproduced in the present study in the energy range 0.3 - 4 eV.[5]

Preliminary experiments on the system $OH^- + D_2O = OD^- + HDO$ revealed anomalous structure in the excitation function at energies of 2 eV and above. This structure was correlated directly with the transmission efficiency of the reactant ion beam through the ion detection system (as reflected in the reactant ion intensity/energy curve). While considerable effort was expended to find a suitable set of operating potentials to eliminate this, the decision was taken to ignore such higher-energy structure since the focus of the present study was on the energy range 0.3 - 1 eV, and the extrapolation to thermal energies.

V. THE SYSTEM: $H_3O^+ + H_2O$

In reactive systems such as this where the reactants and products are identical, extensive use is made of isotopic labelling of the reactants to distinguish the various reaction channels and to identify the dynamic processes occurring in the intermediate of the excited ion cluster. To complement the SIFT studies conducted at 300 K,[3] primary emphasis was given to deuterium labelling of one of the two reactants. Thus five runs were performed on the system $H_3O^+ + D_2O$ and five on the complementary system $D_3O^+ + H_2O$ in the energy range 0.3 - 5 eV. In both cases two channels are open:

$$H_3O^+ + D_2O = HD_2O^+ + H_2O \quad (1)$$

$$= H_2DO^+ + HDO \quad (2)$$

$$D_3O^+ + H_2O = H_2DO^+ + D_2O \quad (3)$$

$$= HD_2O^+ + HDO \quad (4)$$

While there was considerable scatter between the replicate runs, the broad features of the data were well established. Each cross section showed the expected behavior of a monotonic decrease with increasing energy. Each run showed the same trend in the energy dependence of the branching ratios, the details of which are given in Table 1. At the highest energy, channels (1) and (3) were favored, generally by a factor of 3 or 4 to 1, until at the lowest energy they were approximately equal, falling short of the statistical value of 1 to 2, this applying when all hydrogens are completely randomized within the reaction intermediate. Also tabulated are rate constants calculated from total cross sections measured at 0.3 eV and multiplied appropriately by the relative velocity. These show acceptable agreement with the thermal rate constants, measured on the SIFT,[3] and with theoretical predictions,[6] based on the partial alignment of the dipolar molecule to the approaching ion.

TABLE I

Rate Constants (10^{-9} cm^3 $molecule^{-1}$ s^{-1})

	$H_3O^+ + D_2O$	$D_3O^+ + H_2O$
k (0.3 eV)	3 ± 1	1.6 ± 0.2
k (300 K)	2.2	2.0
k_{ADO}	2.3	2.2

Percentage Branching Ratios

Energy	$\sigma_1 : \sigma_2$	$\sigma_3 : \sigma_4$
Thermal (statistical)	33 : 67	33 : 67
0.3 eV	50 : 50	60 : 40
5.0 eV	75 : 25	80 : 20

The data are not independent of the isotopic label employed and the kinetic isotope effect favors slightly a greater predominance of hydrogen scrambling for (1) and (2), where the deuterium fraction is lower.

To gain further insight, one run was made using both oxygen and deuterium labelling.

$$D_3{}^{16}O^+ + H_2{}^{18}O = H_2D^{18}O^+ + D_2{}^{16}O \qquad (5)$$

$$= HD_2{}^{16}O^+ + HD^{18}O \qquad (6)$$

$$= H_2D^{16}O^+ + D_2{}^{18}O \qquad (7)$$

$$= HD_2{}^{18}O^+ + HD^{16}O \qquad (8)$$

$$= D_3{}^{18}O^+ + H_2{}^{16}O \qquad (9)$$

The principal channel (5), the counterpart to (3) involving the discrete transfer of a deuteron, has the same mass as the reactant ion and thus only the four rearrangement ions may be observed. The data are shown in Table II.

TABLE II

Percentage Observable Product Ion Distribution from $D_3{}^{16}O^+ + H_2{}^{18}O$

	Ion (m/e)			
	$DH_2{}^{16}O^+$ (20)	$D_2H^{16}O^+$ (21)	$D_2H^{18}O^+$ (23)	$D_3{}^{18}O^+$ (24)
Statistical	18	38	38	6
Experimental (0.3 - 1 eV)	25	50	25	< 0.1

The characteristic feature of these data is the marked dependence of the cross section on energy, falling below 1 Å^2 above 3 eV. This is precisely what would be expected for those product ions which would require extensive hydrogen rearrangement within the intermediate. The product distribution shows a reasonable approximation to the statistical prediction, with the exception of $D_3{}^{18}O^+$ whose relative abundance is too low. It is tempting to rationalize this result in terms of a simple model, visualizing the products being formed by a sequence of H^+ and/or D^+ exchanges, according to:

$$\begin{array}{ccccccccccc} D_3{}^{16}O^+ & \overset{D^+}{\rightleftharpoons} & DH_2{}^{18}O^+ & \overset{D^+}{\rightleftharpoons} & D_2H^{16}O^+ & \overset{D^+}{\rightleftharpoons} & D_2H^{18}O^+ & \overset{H^+}{\rightleftharpoons} & DH_2{}^{16}O^+ & \overset{D^+}{\rightleftharpoons} & D_3{}^{18}O^+ \\ (22) & & (22) & & (21) & & (23) & & (20) & & (24) \end{array}$$

Thus the explanation for the absence of $D_3{}^{18}O^+$ is that it can arise only after a sequence of five exchanges. The difficulty with this proposal is that there is more m/e = 20 observed than would be expected and less m/e = 23.

VI. THE SYSTEM: $OH^- + H_2O$

Essentially the same data sets were acquired for the prototype negative ion system. Here however there were no prior data at thermal energies, from the SIFT technique, to provide a basis for reference. Again the major emphasis was on the use of deuterium labelling and runs, in triplicate, were made on both the system $OH^- + D_2O$ and $OD^- + H_2O$. Here, in contrast to the system $H_3O^+ + H_2O$, only one reactive channel could be observed, according to

$$OH^- + D_2O = OD^- + HDO \tag{10}$$

$$OD^- + H_2O = OH^- + HDO \tag{11}$$

The agreement between the replicate runs was excellent and, for reaction (10), there was acceptable agreement with a prior run by Paulson in 1971.[5] In both cases the familiar monotonic decrease in the cross section with increasing energy was observed. Data, in the form of rate constants computed from the measured cross sections at 0.3 eV, are shown in Table III together with the theoretical predictions for thermal energy.[6]

TABLE III

Rate Constants (10^{-9} cm^3 $molecule^{-1}$ s^{-1})

	$OH^- + D_2O$	$OD^- + H_2O$
k (0.3 eV)	1.0	1.3
k_{ADO}	2.3	2.3

The kinetic result of interest was the observation of the kinetic isotope effect $\sigma_{11}/\sigma_{10} = 1.30 \pm 0.05$ throughout the energy range investigated, 0.2 - 1.5 eV.

For this system the various reaction channels could only be followed using a combination of deuterium and oxygen - 18 labelling, and one such run was made on the system $^{16}OD^- + H_2{}^{18}O$, for which the following three channels could be observed:

$$^{16}OD^- + H_2{}^{18}O = {}^{18}OH^- + HD^{16}O \tag{12}$$

$$= {}^{16}OH^- + HD^{18}O \tag{13}$$

$$= {}^{18}OD^- + H_2{}^{16}O \tag{14}$$

Cross sections from the rearrangement products, (13) and (14), dropped off steeply with increasing energy while that for the simple particle transfer (12) decreased more gradually. Of particular interest was the dependence of the product distribution upon energy, indicated in Table IV.

TABLE IV

Energy Dependence of Product Distribution for $^{16}OD^- + H_2{}^{18}O$

Energy (eV)	Percentage Product Distribution		
	$^{16}OH^-$	$^{18}OD^-$	$^{18}OH^-$
Statistical	40	20	40
0.4	25	7	68
0.6	23	6	71
0.8	21	5	75
1.0	17	3	80
1.25	13		87
1.5	10		90

Here there is a clear trend towards the statistical distribution as the energy is lowered. Again if one views the rearrangement products arising from a sequence of H^+/D^+ transfers,

$$^{16}OD^- \underset{}{\overset{H^+}{\rightleftarrows}} {}^{18}OH^- \overset{D^+}{\rightleftarrows} {}^{16}OH^- \overset{H^+}{\rightleftarrows} {}^{18}OD^-$$

it is seen that $^{18}OD^-$ requires the most such exchanges and therefore would be expected to depart the most from the statistical prediction.

VII. DISCUSSION AND CONCLUSIONS

All the reactions (1) through (14) may be regarded as being effectively thermoneutral at 300 K and in the energy range of the beam experiments. The basis for this conclusion is the SIFT data on the $H_3O^+ + H_2O$ system where, irrespective of the choice of the deuterium labelling, the product distributions are statistical and the rate constants are identical.[3]

It is appropriate to consider these present beam results in the context of the model formulated from the SIFT data.[3] The model predicts that, for so-called proton-transfer reactions of the type $AH^+ + B = A + BH^+$, the reaction may not consist of the transfer of a proton at all if the reaction is essentially thermoneutral, e.g., if A = B. In such cases the thermochemistry allows the intermediate lifetimes to be long enough at thermal energies ($\sim 10^{-9}$ s) for complete rearrangement of the hydrogens to occur within the intermediate. A necessary condition for the rearrangement to occur is that there be sufficient excitation energy within the intermediate to drive the rearrangement ($\sim$ 20 kcal mol^{-1}): this excitation energy is the interaction energy of the ion AH^+ with the molecule B. Thus scrambling is observed for the system $H_3O^+ + H_2O$[3] (32 kcal mol^{-1}),[7] for $NH_4^+ + NH_3$[8] (17 kcal mol^{-1})[7] and would be predicted for $OH^- + H_2O$ (25 kcal mol^{-1}) at thermal energies; in contrast it is not observed for $CH_5^+ + CH_4$[9] (7 kcal mol^{-1}).[7] In the context of the model the chemical rearrangement processes are determined by the binding energy of the intermediate and its lifetime, and not by the polarity of the ionic charge.

This model makes clear predictions for the processes to be expected in beam studies of such systems, as the relative energy is increased. Increasing the energy decreases the lifetime of the intermediate and therefore the opportunity for rearrangement processes to occur within the intermediate. At high energies only the discrete transfer of a single particle will be possible. Thus the model predicts a change from a statistical distribution at thermal energies to a simple proton transfer at high energies. Again this prediction should apply equally to positive and negative ions.

The results presented in V and VI may now be interpreted in the context of the model. The following conclusions emerge:

1). For both the positive ion system $H_3O^+ + H_2O$ and the negative one $OH^- + H_2O$, the principal mechanism at high energies ($\sim$ 1 eV) consists in the simple transfer of a proton. The intermediate lifetime is too short for rearrangement to occur.

2). For both positive and negative systems, the relative contribution of rearrangement processes increases as the relative energy is reduced. This may be correlated directly with the corresponding increase in the intermediate lifetime.

3). For the positive system the data extrapolate acceptably to the statistical product distribution observed, at thermal energies, from independent SIFT experiments. For the negative system, extrapolation suggests that the same statistical behavior should be found at thermal energies.

4). For the negative system, the extent of the rearrangement within the intermediate increases as the energy is reduced and the lifetime increased. In contrast, for the positive system, the relative contributions of the individual rearrangement products do not vary with energy. This suggests that, wherever rearrangement occurs, it is more facile for the positive system than the negative: this may perhaps be correlated with the two binding energies.

5). At the lowest energies in the beam experiments (~ 0.3 eV), the product distributions in both cases are far from statistical. This result is compatible with simple model calculations of the dependence of the intermediate lifetime upon energy.[10] A lifetime of 10^{-9} s at 300 K decreases to 10^{-12} s at an energy of 0.3 eV.

6). For both systems a kinetic isotope effect is observed throughout the energy range, favoring H^+ in comparison with D^+ both in direct transfer and in rearrangement within the intermediate. This disappears for the positive system at thermal energies. A necessary test for the applicability of the model to the negative system is therefore a comparable disappearance of the kinetic isotope effect at thermal energies.

VIII. RECOMMENDATIONS

A start has been made on the objectives listed in Section II above. Given the preliminary nature of certain of the data, it may fairly asserted that the model, formulated recently for so-called proton-transfer reactions involving positive ions at thermal energies, may be extended to the negative ion-molecule system investigated here and to the energy dependences of both.

The next stages of this investigation will consist of the following:

1). For the $H_3O^+ + H_2O$ system, certain of the experimental data show an unacceptable scatter and these will be refined.

2). In both the systems studied, considerable insight came from the oxygen-18 labelling experiments. The full complement of these will be completed, specifically: $H_3{}^{18}O^+ + H_2{}^{18}O$, $H_3{}^{18}O^+ + H_2{}^{16}O$, $H_3{}^{18}O^+ + D_2{}^{16}O$ and ${}^{16}OH^- + H_2{}^{18}O$, ${}^{18}OH^- + H_2{}^{16}O$, ${}^{18}OH^- + D_2{}^{16}O$.

3). The study will be extended to include the reactions of the hydrates $H_3O^+(H_2O) + H_2O$ and $OH^-(H_2O) + H_2O$.

4). The SIFT technique will be used to study the systems $OH^-(H_2O)_{0,1,2} + H_2O$ at thermal energies.

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FINAL REPORT

DETONATION PHYSICS OF NONIDEAL EXPLOSIVES WITH ANALYTICAL RESULTS FOR DETONATION FAILURE DIAMETER

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ABSTRACT

The main causes of nonideal behavior in explosives are examined. An elaboration of the ZND model for 1-dimensional steady detonations is presented as a reference frame from which to examine the effects of reversible chemical reactions endothermic reactions, etc. Mathematical models for 2-dimensional detonations are studied and a preliminary analytical method of solution is presented. The method provides analytical expressions for the detonation failure diameter in terms of the parameters of the detonation. The results obtained help to clarify previous results obtained by other authors using numerical methods. Suggestions for further research are given.

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I. INTRODUCTION

The most powerful high explosive formulations are usually composed of TNT, HMX, RDX and a few other compounds. These substances are relatively expensive and their availability in large quantities is not assured. To head-off a possible shortage of high explosive materials, attempts are being made by the USAF and others to increase the variety of compounds that can be used as high explosive components. Due to its wide availability, ammonium nitrate is one of the most important compounds being incorporated into new high explosive formulations. It is often found that these new formulations do not perform as well as one would expect from their heats of reaction and other thermodynamic data. This deficient performance has led to the use of the term nonideal explosives.

There is no hard definition of nonideal explosives. The situation is similar to that for ideal vs. nonideal gases. A nonideal gas is one whose equation of state differs significantly from the ideal gas law PV=NKT. No real gas is ideal if one looks hard enough, but under the usual conditions of low pressure and high temperature, however, most gases behave very closely to ideal gases. In the case of explosives, ideal behavior is pretty well represented by the Chapman-Jouguet (CJ) theory of detonations. In many cases, where one deals with explosives with fast reaction rates and large diameter charges. There is good agreement between the CJ theory and experiment. In many of the new explosive formulations being developed, however, one finds nonideal behavior. In these nonideal explosives the detonation velocity and pressure are found to be significantly lower than predicted by the CJ theory. This disagreement between theory and experiment has prompted the need for further developments in detonation theory.

The Chapman[1] - Jouguet[2] theory was developed near the turn of the century. There are many good expositions of it such as by Courant and Friedrichs[3] and by Taylor and Tankin[4]. The CJ theory considers the reaction zone to be a discontinuity in a reacting gas, very similar to the usual theory of gas-dynamic shocks. The fluid-flow equations for conservation of mass, momentum and energy are integrated across a 1-dimensional plane detonation discontinuity.

The above is completed with the hypothesis that immediately behind the discontinuity the chemical reactions are completed, and the fluid velocity relative to the discontinuity is sonic. The CJ theory will not be discussed in detail here because more advanced developments are presented below. To compare this theory with experiment one needs the equation of state and the energy equation of the explosive. These equations are not well known for solid explosives. This is typical of the present state of the field, where a lot of important information is just not known. The situation for gases is much better than it is for solids, and satisfactory comparisons between theory and experiment can be made.

The next major step forward in the understanding of detonations took place during World War II with the development of the Zeldovick-Von Neumann[5]-Doering (ZND) theory of detonations. A thorough discussion of this theory as well as many theoretical and experimental aspects of detonations can be found in the recently published book by Fickett and Davis[6]. Von Neumann's rigorous treatment of a 1-dimensional steady detonation wave firms up and clarifies the CJ theory. His discussion of a pathological reaction also introduces a way in which nonideal behavior can occur. His model of a detonation wave is that it consists of a mechanical shock wave that initiates the chemical reaction, followed by a deflagration zone (pressure drops away from shock) where the chemical energy is released.

Present theories for steady detonation waves are extensions of the ZND theory. They include general types of chemical reactions and deviations from 1-dimensional motion. These effects are the main causes of nonideal behavior and will be considered below. This work is organized as follows. Sec II states the research objectives. Sec. III presents a discussion of a fairly general theory of steady detonations. In Sec. IV the theory is specialized to 1-dimensional detonations to highlight the nonideal effects due to various types of chemical reactions. In Sec V the effects of divergent flow are explored. These effects are quite complicated to calculate because the flow is no longer 1-dimensional. This section contains the original results on detonation failure obtained in this research effort. Sec. VI contains the conclusions and recommendations.

II. OBJECTIVES OF THE RESEARCH EFFORT

(1) To survey the present state of detonation theory with a view to obtain a clear understanding of the causes of nonideal behavior in explosives.

(2) To develop analytical methods for obtaining solutions to some of the problems of interest. Specifically, an approximation method is studied that can lead to analytical expressions for calculating the detonation failure diameter of detonating charges.

III. GENERAL DISCUSSION

As the front of a detonation wave passes a point, it leaves behind a gas moving with some velocity. The set of points where the speed of the moving gases relative to the front equals the local speed of sound is called the sonic locus. The strength of the detonation wave depends on the amount of chemical energy that is released between the leading shock front and the sonic locus. Any chemical energy released beyond the sonic locus is lost for the purpose of producing a strong detonation wave although it may still do useful work against confining media. As will be seen below, the CJ theory predicts that in many cases the sonic locus coincides with the point where the chemical reaction is completed so the entire energy released is applied to the detonation wave. Any deviation from this will amount to nonideal behavior. In order to understand the problem one should start with a fairly general model. A good framework is given in the papers of Kirkwood and Wood[7] and Wood and Kirkwood[8]. An even more general starting point is found in Chapters 4 and 5 of Ref. 6. The mathematical model uses the Euler equations for a compressible, nondissipative, reactive medium, undergoing adiabatic motion into which a steady detonation wave is propagating. Let the medium be a cylinder of indefinite length but finite radius. We introduce a system of cylindrical coordinates with Z-axis along the charge axis. The region $Z < 0$ will cover the unreacted explosive. The shock front is at $Z=0$ at $t=0$ and propagates toward $Z < 0$. The region $Z > 0$ covers the zone of reaction. The variables are taken to be independent of the azimuthal angle around the Z=axis.

The equations are:

$$\dot{\rho} + \rho\left(\frac{\partial u}{\partial z} + \frac{\partial \omega}{\partial r}\right) + \rho\frac{\omega}{r} = 0 \quad , \qquad (1)$$

$$\rho\dot{u} + \frac{\partial p}{\partial z} = 0 \quad , \qquad (2)$$

$$\rho\dot{\omega} + \frac{\partial p}{\partial r} = 0 \quad , \qquad (3)$$

$$\dot{E} - p\frac{\dot{\rho}}{\rho^2} = 0 \quad , \qquad (4)$$

and $$\dot{\lambda}_i = R_i = F_i(1-\lambda_i) \quad , \quad i = 1, \ldots, j \, . \qquad (5)$$

Here ρ is the mass density; u and ω are the mass velocity components in the Z and r directions respectively; p is the fluid pressure; E is the internal energy per unit mass; and the λ_i are a set of reaction progress variables for the j chemical reactions taking place with the reaction rates R_i. An equation of state $E = E(p\ \rho, \lambda_i)$ is assumed known. A form often used is

$$E(p, \rho, \lambda_i) = \frac{p}{\rho(\gamma-1)} - \sum_{i=1}^{j} \lambda_i q_i \qquad (6)$$

where the q_i are the heats per unit mass released in the reactions. The dot (.) notation means that the connective derivative is taken

$$\cdot \equiv \frac{\partial}{\partial t} + u\frac{\partial}{\partial z} + \omega\frac{\partial}{\partial r} \qquad (7)$$

We will just consider a steady detonation wave located at Z=0. The unreacted fluid rushes in from the left with a detonation speed D (to be determined). We also specialize the equations to the Z axis where r=0 and ω=0. The result is

$$u\frac{\partial\rho}{\partial z}+\rho\frac{\partial u}{\partial z}=-2\rho\frac{\partial\omega}{\partial r} \quad , \qquad (8)$$

$$\rho u\frac{\partial u}{\partial z}+\frac{\partial p}{\partial z}=0 \quad , \qquad (9)$$

$$\frac{\partial p}{\partial r}=0 \quad , \qquad (10)$$

$$\frac{\partial E}{\partial z}-\frac{p}{\rho^2}\frac{\partial\rho}{\partial z}=0 \quad , \qquad (11)$$

and
$$u\frac{\partial\lambda_i}{\partial z}=R_i \quad , \quad i=1,\ldots,j. \qquad (12)$$

The Von Neumann model is to assume that for $Z < 0$ the flow quantities are constant with values ρ_0, p_0, $D=u_0$, $\lambda_i=0$. At $Z=0$ there is a mechanical shock with jumps to ρ_1, p_1, u_1 but still $\lambda_i=0$. For $Z>0$ the reactions develop accompanied by changes in ρ, p, and u. The Mach numbers

$$M_0=\frac{D}{c_0} \quad , \qquad (13)$$

Where c_0 is the sound speed in front of the shock, and

$$M_1=\frac{D}{c_1} \quad , \qquad (14)$$

Where c_1 is the sound spped right behind the shock, are related by

$$M_1^2=\frac{2+(\gamma-1)M_0^2}{2\gamma M_0^2-(\gamma-1)} \quad , \qquad (15)$$

in accordance with the usual shock relations

$$\frac{p_1}{p_0}=\frac{2\gamma M_0^2-(\gamma-1)}{\gamma+1}=q \quad , \qquad (16)$$

and
$$\frac{\rho_1}{\rho_0}=\frac{(\gamma+1)M_0^2}{2+(\gamma-1)M_0^2} \quad , \qquad (17)$$

as found in Landau and Lifshitz[9]. A solution of the shock conditions with no discontinuity, so $p_1 = p_0$, $\rho_1 = \rho_0$, and $M_1 = M_0$, is also allowed. Eq. (8) - (11) can be integrated with the boundary conditions at $Z=0^+$ and $Z=0^-$

$$\rho(0^+) = \rho_1 \; , \; p(0^+) = p_1 \; , \; u(0^+) = u_1 \quad ,$$

$$\rho(0^-) = \rho_0 \; , \; p(0^-) = p_0 \; , \; u(0^-) = D \quad , \quad (18)$$

to yield

$$\rho_0 D = \rho_1 u_1 = \rho u + 2\rho_0 D I_2 \quad , \quad (19)$$

$$\rho_0 D^2 + p_0 = \rho_1 u_1^2 + p_1 = \rho u^2 + p + 2\rho_0 D^2 I_3 \quad , \quad (20)$$

and

$$H_0 + \tfrac{1}{2} D^2 = H_1 + \tfrac{1}{2} u_1^2 = H + \tfrac{1}{2} u^2 \quad , \quad (21)$$

where H is the enthalpy per unit mass,

$$H = E + p/\rho \quad , \quad (22)$$

and

$$I_2 = \frac{1}{\rho_0 D} \int_0^z \rho \frac{\partial \omega}{\partial r} dz \quad , \quad (23)$$

and

$$I_3 = \frac{1}{\rho_0 D^2} \int_0^z \rho u \frac{\partial \omega}{\partial r} dz \quad , \quad (24)$$

in the notation of Chapter 5 of Ref. 6. The integrals I_2 and I_3 represent losses due to the radially divergent flow. In one dimensional flow they would be zero. Bernoulli's equation along the axis, Eq. (21), is not affected by the radial flow. The important equation

$$\frac{\partial u}{\partial z} = \frac{\sum_i \sigma_i R_i - 2\,\partial\omega/\partial r}{1 - u^2/c^2} \quad , \quad (25)$$

can be obtained from Eqs.(8)-(12). The σ_i are given by

$$\sigma_i = \frac{1}{\rho c^2} \left(\frac{\partial p}{\partial \lambda_i}\right)_{E,\rho,\lambda_j} \quad , \quad (26)$$

with

$$c^2 = \frac{1}{\rho^2} \frac{(p - \rho^2\,\partial E/\partial\rho)}{\partial E/\partial p} = \left(\frac{\partial p}{\partial \rho}\right)_{s,\lambda} \quad . \quad (27)$$

The above equations can describe the steady flow region.Eq. (25) has a singularity at $u=c$, the sonic locus. Beyond this point the flow has to match the boundary conditions at Z large. Generally the flow beyond the sonic locus is some sort of time dependent rarefaction wave. Fig. 1 is a diagram of the situation.

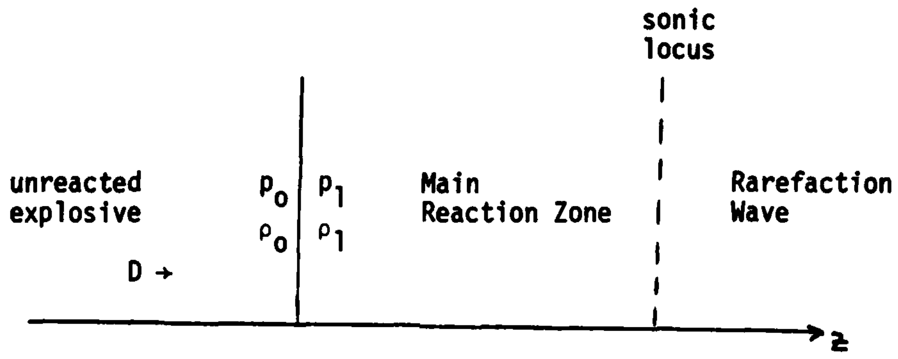

Fig. 1. Main regions of a detonation wave seen in the frame of the shock front.

The equations in this section allow for a fairly realistic and mathematically very complicated model. In Sec. IV we specialize the equations to the much simple 1-dimensional flow where $\omega=0$. In Sec. V we consider some aspects of 2-dimensional flows.

IV. 1-DIMENSIONAL THEORY

Putting $\omega=0$ and $\partial/\partial r=0$ in the equations of Sec. III we obtain a 1-dimensional theory. The results of this section are standard and are presented to fix the notation and nomenclature that is needed in Sec.V. Eliminating u from Eq. (19) and (20) one obtains

$$p-p_0 = \rho_0^2 D^2 \left(1/\rho_0 - 1/\rho \right) \quad .(28)$$

In a p vs. $1/\rho$ plot, the graph of Eq. (28) is a straight line called the Rayleigh line. Eliminating u and D from Eq. (21) one obtains

$$E(p,\rho,\lambda_i) - E(p_0,\rho_0,0) = \tfrac{1}{2}(p+p_0)\left(1/\rho_0 - 1/\rho \right), \quad (29)$$

which is a family (as one varies λ_i) of curves, in a p vs. $1/\rho$ plot, known as Hugoniot curves. As we move in Z behind the front, the λ_i are related because from Eq. (12) we have

$$\frac{d\lambda_1}{R_1} = \frac{d\lambda_2}{R_2} = \cdots\cdots = \frac{d\lambda_j}{R_j} \quad . (30)$$

Thus in effect a single λ parametrizes the Hugoniot family. So far D is not determined so the slope of the Rayleigh line ($-\rho_0^2 D^2$) is unknown. Yet the intersection of the Rayleigh line with the Hugoniot curves will determine the solution. The answer is obtained by noting that Eq. (25) gives a singularity for $\partial u/\partial z$ at the sonic locus unless we have

$$\sum_{i=1}^{j} \sigma_i R_i = 0 \quad . (31)$$

(we are in 1-dimension, so $\omega=0$). Eq. (31) must be imposed at the sonic locus to avoid the singularity for the reasons given in Chapter 5 of Ref. 6. Eq. (31) determines the value of the λ_i and thus picks a particular Hugoniot curve, at the sonic locus. Noting that $u=c$ at the sonic locus, and using Eq. (19), we have that the slope of the Rayleigh line is

$$-\rho_0^2 D^2 = -\rho^2 c^2 \quad . \tag{32}$$

We also have that the slope of the Hugoniot curves is

$$\left.\frac{\partial p}{\partial(1/\rho)}\right|_{\mathcal{H}} = -\frac{\left[\frac{1}{2}(p+p_0) - \rho^2\, \partial E/\partial\rho\right]}{\left[\partial E/\partial\rho - \frac{1}{2}(1/\rho_0 - 1/\rho)\right]} \quad . \tag{33}$$

Combining Eqs. (27), (32), and (33), we get for the slope of the Hugoniot curves

$$\left.\frac{\partial p}{\partial(1/\rho)}\right|_{\mathcal{H}} = -\rho^2 c^2 \quad . \tag{34}$$

Thus, the slope of the Rayleigh line is the same as the slope of the Hugoniot curve (which is determined by Eq. (31)) at the sonic locus. For the case where there is only one reaction Eq. (31) becomes R=0 or λ=1 at the sonic locus. This means that the one reaction is completed at the sonic locus. This justifies the CJ hypothesis which determines the Rayleigh line (and thus D) by putting it tangent to the completed reaction Hugoniot. For the equation of state of Eq. (5), the above method yields that D satisfies

$$D^4 - 2D^2 c_0^2\left[1 + \frac{\lambda q(\gamma^2-1)}{c_0^2}\right] + c_0^4 = 0 \quad . \tag{35}$$

Eq. (35) has the two roots

$$D_\pm^2 = c_0^2 M_{0\pm}^2 = c_0^2\left\{1 + \lambda q\frac{(\gamma^2-1)}{c_0^2} \pm \sqrt{\left[1 + \lambda q\frac{(\gamma^2-1)}{c_0^2}\right]^2 - 1}\right\} \quad . \tag{36}$$

The two roots give two Rayleigh lines called R+ and R-. R+ represents a CJ detonation while D- represents a CJ deflagration. These are depicted in Fig. 2. For the CJ- solution the solution goes smoothly along R- from to the values at CJ- attained at the sonic locus. No shock takes place for this deflagration solution. For the detonation, the Von Neumann model is that the solution goes along the no reaction Hugoniot from 0 to N, $p=p_1$ and $\rho=\rho_1$ (with p_1 and ρ_1 determined from Eqs. (16) and (17) using Eq (36) for M_0) and then down from N to CJ+ along R+; A detonation solution going directly from

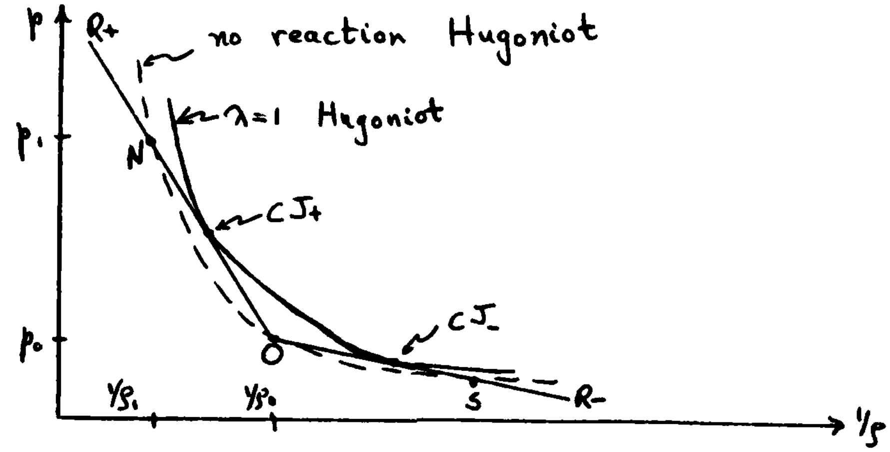

Fig. 2. The p- $^1/\rho$ plane. CJ+ gives the pressure at the sonic locus for a detonation. CJ- gives the pressure for a deflagration

0 to CJ+ along R+ with no shock is also allowed. Both solutions have the same final state CJ+ at the sonic locus and the same D. The no shock solution does not usually occur because of problems with initiating the reaction. The Von Neumann model in fact says that the 0→CJ+ detonation is actually a mechanical shock to p_1 followed by a deflagration from N to CJ+. Due to the way that the equations integrate through a shock, the point CJ+ is the same with or without a Von Neumann spike.

The CJ hypothesis is that the sonic locus is determined by tangency of the Rayleigh line to the completed reaction Hugoniot. If there are several irreversible exothermic reactions this hypothesis is correct (for 1-dimensional, steady flows). If some of the reactions are reversible, however, or if some of the σ_i may be negative as in mole decrement reactions, then Eq. (31) does not imply that the reactions are completed at the sonic locus.

Thus some of the chemical energy is released beyond it. This late energy is not effective in the detonation and nonideal behavior is found. The analysis of precisely what happens involves a study of the phase plane of Eq. (25). Many complicated results are possible depending on the details of the σ_i and the R_i. A fairly thorough discussion of the possibilities can be found in chapter 5 of Ref. 6, and in Wood and Salsburg[10].

This brief discussion of steady, 1-dimensional detonations does not cover the entire subject. In this research effort we have made no contribution to this part of the field. There are good analytical methods, that supplemented by computer calculations, can predict the nonideal performance of steady, 1-dimensional detonations. An input to these methods, however, must contain a realistic description of the reaction kinetics. This is presently not known for most gaseous explosives, let alone solid ones. In the case of solid explosives, beyond the lack of information concerning the equation of state and the reaction kinetics, there are also the problems associated with inhomogeneous mixtures. Here the effects due to grain burning and diffusion of reactants are not fully worked out.

V. DIVERGENT FLOW AND DETONATION FAILURE

When ω is not negligible, Egs. (8)-(12) need to be complemented by a way to compute $\frac{\partial \omega}{\partial r}$ as a function of Z. This depends on the shape of the exploding charge and on the properties of the confining media. In general, to compute ω one must solve a difficult free boundary problem with matching at the boundary to account for the properties of the different media. Even if ω were known, however, there are still some interesting difficulties in integrating Eqs. (8)-(12). These equations should predict the observed phenomenon of detonation failure when the diameter of the exploding cylinder is small. We will cast those equations in the form for flow in a nozzle by letting

$$\frac{1}{A}\frac{dA}{dz} = \frac{2}{u}\frac{\partial \omega}{\partial r} , \quad (37)$$

where A is the area of the nozzle. The equations become

$$\frac{d}{dz}(\rho u A) = 0 \quad , \tag{38}$$

$$\frac{du}{dz} = \frac{\sum_{i=1}^{j} \sigma_i R_i - \frac{u}{A}\frac{dA}{dz}}{1 - u^2/c^2} \quad , \tag{39}$$

$$\frac{d\lambda_i}{dz} = R_i/u \quad , \tag{40}$$

and $$\frac{d}{dz}\left(H + u^2/2\right) = 0 \quad . \tag{41}$$

Several authors have taken the above equations with realistic rate terms and applied computer methods to obtain a variety of results. Some of this work is summarized in Chapter 5 of Ref. 6. Wecken" takes

$$\frac{1}{A}\frac{dA}{dz} = \epsilon = \text{constant} \quad , \tag{42}$$

with one Arrhenius reaction to discuss the structure of the reaction zone. He is not successful in obtaining detonation failure at some critical ε because of computational difficulties. Tsuge et al.[12] take

$$\frac{dA}{dz} = \frac{1}{\sigma_1}\left[\frac{Pg - A}{(1+\gamma k M_0^2)A - Pg}\right]^{1/2} \quad , \tag{43}$$

where σ_1 is the value of the thickness σ of an explosive slab at Z= 0,g is given in Eq. (16) ,

$$A = \frac{\sigma}{\sigma_1} \quad , \quad P = \frac{p}{p_1}A \quad , \quad \text{and} \quad k = \frac{\rho_{00}}{\rho_0} \quad , \tag{44}$$

where ρ_{oo} is the density of the confining medium. Eq. (43) is obtained by treating the lateral expansion as a blunt body about which the confining inert flows. Tsuge et al. take a very detailed description of the reaction kinetics for $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ and solve the problem numerically. Their comparisons with experiment for exploding slabs are fairly good. Their numerical calculations lead to plots as shown in Fig. 3. For $\sigma_1 < \sigma_c$ there is no detonation solution, so detonation failure is found in this model. For $\sigma_1 > \sigma_c$ they obtain two solution branches. The upper branch is like the usual 1-dimensional detonation M_{0+} of Eq. (36). They did not explore the lower branch fully because of computational difficulties. They speculate that as $\sigma_1 \rightarrow \infty$ the lower branch has $M_0 \rightarrow 1$. It will be shown here that this is incorrect. The limit of the lower branch as $\sigma_1 \rightarrow \infty$ is actually $M_0 \rightarrow M_{0-}$ as in Eq. (36).

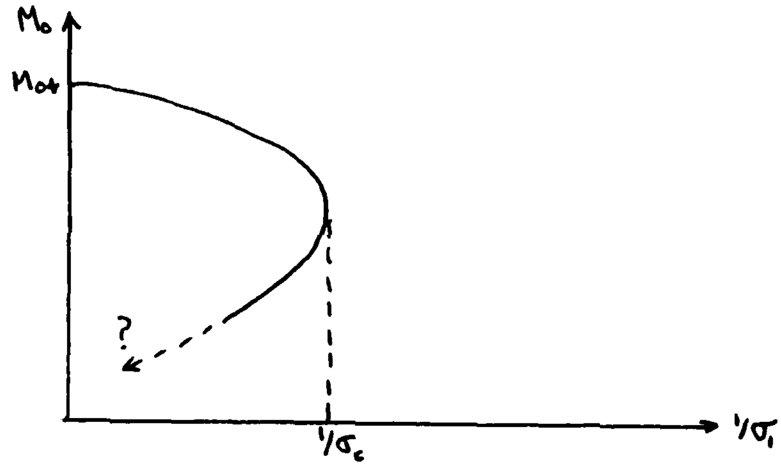

Fig. 3. Rough plot of Mo vs. $1/\sigma$ in Tsuge et al.[12]

Rather than attacking this problem numerically from the beginning we will try to develop the solution analytically as far as possible. We use the equation of state given in Eq. (6). Then the σ_i defined in Eq. (26) (not to be confused with the σ and σ_1 above which were lengths) are given by

$$\sigma_i = \frac{(\gamma-1)}{c^2} q_i \quad , \quad (45)$$

where

$$c^2 = \frac{\gamma p}{\rho} = \frac{2(\gamma-1)}{2+(\gamma-1)M^2}\left[\sum_i \lambda_i q_i + H + u_i^2/2\right] . \quad (46)$$

We rewrite Eq. (39) as

$$\frac{2(1-m)}{m(1+\gamma m)[2+(\gamma-1)m]}\frac{dm}{dz}=\frac{\frac{d}{dz}\sum_i \lambda_i q_i}{\sum_i \lambda_i q_i + H_i + u_i^2/2}-\frac{2}{1+\gamma m}\frac{1}{A}\frac{dA}{dz}\ ,$$

where $m = M^2 = u^2/c^2$. (47)

Eq. (47) is to be solved so that dm/dz remains finite at $m=1$. A necessary condition for this is that the right hand side of Eq. (47) be zero when $m=1$. Also at $Z=0$, $\lambda=0$ and $m=m_1$ with m_1 to be determined. These are unusual boundary conditions to impose on a first order ordinary differential equation. Eq. (47) does not satisfy the usual Lipschitz condition needed for the existence of a solution with a desired value of m at a specific Z . But the unusual boundary conditions are sufficiently "free" that a solution will exist. We do not fix the Z where $m=1$ occurs, the sonic point Z, but we let the equation tell us so as to keep dm/dz finite. Then we find the value m_1 . Since the problem presented by Eq. (47) is not a standard one it is unclear that a Picard iteration method will converge for it. We have found useful results with this method, so we will use it with the awareness that it may need modification due to convergence difficulties. The n^{th} iteration of m, m^n will be found from

$$\frac{2(1-m^n)}{m^n(1+\gamma m^n)[2+(\gamma-1)m^n]}\frac{dm^n}{dz}=\frac{\frac{d}{dz}\sum_i \lambda_i^n q_i}{\sum_i \lambda_i^n q_i + H_i^n + u_i^{n2}/2}-\frac{2}{1+\gamma m^{n-1}}\frac{1}{A}\frac{dA}{dz}\ , \quad (48)$$

where n = 2,3,....

with the right hand side of Eq. (48) equal to zero when $m^n = 1$. We also need to use Eq. (40). The first iterate m^1 is found by putting the dA/dz term equal to zero. The equation for m^1 can be integrated to get

$$\frac{m'\left[2+(\gamma-1)m'\right]\left[1+\gamma m_1'\right]^2}{(1+\gamma m')^2\, m_1'\left[2+(\gamma-1)m_1'\right]} = \frac{\sum_i \lambda_i q_i + \frac{c_1^2}{2(\gamma-1)}\left[2+(\gamma-1)m_1'\right]}{\frac{c_1^2}{2(\gamma-1)}\left[2+(\gamma-1)m_1'\right]} \;, \quad (49)$$

where $$m_1' = m'(z=0) \;, \quad (50)$$

and where we have used Eq. (46) evaluated at $Z=0$, with $c_1 = c(Z=0)$. Imposing the right hand side condition for the m equation we get

$$\frac{d}{dz}\sum_{i=1}^{j} \lambda_i q_i = 0 \quad \text{at} \quad m' = 1 \;. \quad (51)$$

If all the q_i are positive, and the R_i are as given in Eq. (5), we need that for the first iteration, at the sonic point Z_s^1,

$$m'(z_s') = 1 \;, \quad \lambda_i(z_s') = 1 \;. \quad (52)$$

For the simple R_i this implies $Z_s^1 = \infty$. We go to Eq. (49) and put $\lambda_i = 1$ when $m^1 = 1$ to find m_1^1. The result is that m_1^1 obeys the equation

$$\frac{(1+\gamma)(1+\gamma m_1')}{(1+\gamma)^2\, m_1'} = \left[2+(\gamma-1)m_1'\right] + \frac{2(\gamma-1)}{c_1^2}\sum_i q_i \;. \quad (53)$$

Manipulating this equation yields

$$(m_1')^2 - 2m_1'\left[1 + \frac{(\gamma^2-1)}{c_1^2}\sum_i q_i\right] + 1 = 0 \;. \quad (54)$$

Eq. (54) is almost the same as Eq. (35). The difference is that in Eq. (35) we have c_0 and $D= M_0 c_0$ whereas c_1 appears in Eq. (54). If we consider the case with no shock, then $c_1 = c_0$, $m_1^1 = m_0^1$, and we have the same result as in Eq. (35). The solutions obtained would refer to a no-shock detonation that goes along O-CJ+ and a no-shock deflagration that goes along O-CJ-. The second of these is meaningful, but not the first. If we consider the case with a shock we put

$$c_1^2 = \frac{\gamma p_1}{\rho_1} = \frac{\gamma p_0}{\rho_0} \frac{\left[2\gamma m_0^1 - (\gamma-1)\right]\left[2 + (\gamma-1) m_0^1\right]}{(\gamma+1)^2 \, m_0^1} \tag{55}$$

into Eq. (54) to get, after using Eq. (15),

$$(m_0^1)^2 - 2 m_0^1 \left[1 + \frac{\gamma^2 - 1}{c_0^2} \sum_i q_i \right] + 1 = 0 \quad . \tag{56}$$

This is exactly the same as Eq. (35), just as it should be because the R+ line in Fig. 2 is the same whether we consider a shock solution along $O\text{-}N\text{-}CJ_+$, or a no shock one along $O\text{-}CJ_+$. The two solutions of Eq. (56) are interpreted as a Von Neumann detonation along $O\text{-}N\text{-}CJ_+$, and an unphysical shocked deflagration along O-S-CJ-. Out of the four solutions obtained we only desire the shocked detonation $O\text{-}N\text{-}CJ_+$, and the no-shock deflagration O-CJ-. Their detonation velocities are given by the roots $D_+ = c_0 M_{0+}$ and $D_- = c_0 M_{0-}$ of Eq. (35). Using Eq. (15) we get the m_{1+}^1 that goes with M_{0+} while the m_1^1 that goes with M_{0-} is $m_{1-}^1 = M_{0-}$. Knowing m_{1+}^1 and m_{1-}^1 we go to Eq. (49) and we get m_+^1 and m_-^1 as functions of $\lambda_1(z)$. Finally from Eq. (40) we can integrate to get $\lambda^1(z)$. This first iterate reproduces the results of Sec. IV because dA/dz was neglected. But we begin to see the source of the two roots in the work of Tsuge et al.[12] When we compute the next iteration the results of the expansion will come in. But as the diameter goes to ∞ the expansion becomes negligible and the results reduce to m_+^1 and m_-^1. To compute m^2 we go to Eq. (48) with n=2. We integrate it with the boundary condition

$$m^2(z=0) = m_1^2 \quad . \quad (57)$$

The result is

$$\ln\left\{\frac{m^2[2+(\gamma-1)m^2](1+\gamma m_1^2)^2}{(1+\gamma m^2)^2 m_1^2[2+(\gamma-1)m_1^2]}\right\} = \ln\left\{\frac{\sum_i \lambda_i^2 q_i + H_1^2 + (u_1^2)^2/2}{H_1^2 + (u_1^2)^2/2}\right\} - 2\int_0^z \frac{1}{1+\gamma m^1}\frac{1}{A}\frac{dA}{dz}dz \; .$$

(58)

m_1^2 is determined by imposing the bounded dm^2/dz condition to the right hand side of Eq. (48) with n=2. At the sonic point z_s^2 we have

$$\frac{1}{\sum_i \lambda_i^2 q_i + H_1^2 + (u_1^2)^2/2} \sum_i q_i \frac{(1-\lambda_i^2)F_i}{c}\bigg|_{z_s^2} = \frac{1}{1+\gamma m^1}\frac{1}{A}\frac{dA}{dz}\bigg|_{z_s^2} \quad . \quad (59)$$

Eq. (40) was used to obtain Eq. (59). The latter equation says that $\lambda_i \neq 1$ at the sonic point so the reactions are not completed. Some of the energy will be released late leading to nonideal behavior. In principle Eq. (59) determines Z_s^2 in terms of m_1^2 . This can be seen as follows. We have that

$$\frac{(c)^2}{\gamma-1} + \frac{(u)^2}{2}\bigg|_{z_s^2} = H_1 + \frac{(u_1)^2}{2} = \frac{(c)^2}{\gamma-1} + \frac{(c)^2}{2}\bigg|_{z_s^2} \quad , \quad (60)$$

so that c in Eq. (59) is known in terms of m_1^2 and c_1 . Also from Eq. (40)

$$\frac{d\lambda_i^2}{dz} = \frac{R_i}{m^2 c} \quad . \quad (61)$$

In Eq. (61) m^2 is known in terms of λ^2 from Eq.(58) . (We assume that $\frac{1}{A}$ dA/dz is explicitly known as a function of Z). Therefore one can integrate Eq. (61) to get λ^2 as a function of Z and m_1^2 . When this function $\lambda^2(Z, m_1^2)$ is substituted into Eq. (59) one can find Z_s^2 as a function of m_1^2 as claimed. Now we go back to Eq.(58) and demand that

$$m^2(z_s^2) = 1, \quad \lambda_i^2(z_s^2) = \lambda_i^2(z, m_1^2) \equiv \lambda_{is} , \quad (62)$$

and get

$$\frac{(1+\gamma m_1^2)^2}{(1+\gamma)\, m_1^2} = 2 + (\gamma-1) m_1^2 + \frac{2(\gamma-1)}{(C_1)^2} \sum_i \lambda_s q_i - 2\left[2+(\gamma-1)m_1^2\right] \int_0^{z_s^2} \frac{1}{1+\gamma m'} \frac{1}{A}\frac{dA}{dz}\, dz . \quad (63)$$

In Eq. (63) Z_s^2 and λ_s^2 are functions of m_1^2 . So Eq. (63) is an equation for m_1^2 . The last terms is the expansion dependent term. Let

$$\Delta(\epsilon) = 2 \int_0^{z_s^2} \frac{1}{1+\gamma m'} \frac{1}{A}\frac{dA}{dz}\, dz \quad . \quad (64)$$

Here ε represents an inverse diameter that goes to zero as the diameter goes to ∞ . Also $\Delta(\varepsilon) \to 0$ as $\varepsilon \to 0$ or as the expansion is negligible. Eq. (63) is rewritten as

$$(m_1^2)^2\left[1+(\gamma^2-1)\Delta\right] - 2\, m_1^2\left[1 + \frac{\gamma^2-1}{(C_1)^2}\sum_i \lambda_{is} q_i - \Delta(1+\gamma)\right] + 1 = 0 \quad . \quad (65)$$

This equation reduces to Eq. (54) as $\Delta \to 0$ and $\lambda_s^2 \to 1$ as $\varepsilon \to 0$. Thus there is a clear connection between the two branches to be obtained from Eq. (65) and thel-dimensional results. The two roots of Eq. (65) are obtained by the quadratic formula as

$$m_1^2 = \frac{\left[1+\frac{(\gamma^2-1)}{(C_1)^2}\sum_i \lambda_{is} q_i - \Delta(1+\gamma)\right] \pm \sqrt{\left[1+\frac{(\gamma^2-1)}{(C_1)^2}\sum \lambda_{is} q_i - \Delta(1+\gamma)\right]^2 - \left[1+\Delta(\gamma^2-1)\right]}}{\left[1+\Delta(\gamma^2-1)\right]} . \quad (66)$$

For small ε these two roots give the m_+^1 and m_-^1 of before which were connected with the m_{0+}^1 and m_{0-}^1 of Eq.(35). As ε and Δ grow beyond a critical value the two roots become complex, so there is no real solution and detonation failure takes place. To simplify things let us ignore the variation of λ_s^2 with ε. Then a plot of the roots versus Δ appears as in Fig. 4. This is qualitatively the same as the curve

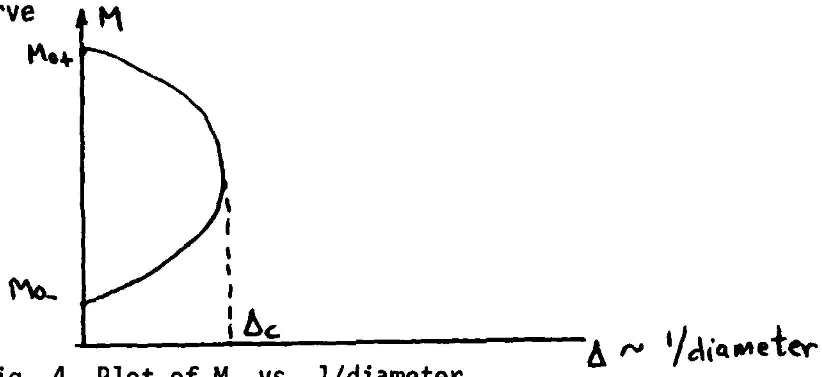

Fig. 4. Plot of M_0 vs. 1/diameter.

obtained numerically by Tsuge et al. For $\Delta < \Delta_c$ (for the diameter greater than some critical value) there are two branches. The upper branch is connected as $\Delta \to 0$ to the 1-dimensional shocked detonation 0-N-CJ_+ of Fig. 2. The lower branch is connected as $\Delta \to 0$ to the 1-dimensional no-shock deflagration 0-CJ_- .Now one sees the error in the work Tsuge et al. They could compute things like Z_s^2 and λ_s^2 numerically but with so much difficulty that the results were hard to interpret.

The qualitative features of the solution are now clear. To get quantitative results one needs to integrate Eq. (61). This would have to be done numerically. It is clear that successive steps in the iteration are not very different from the steps to calculate m^2 . No theoretical problems with convergence should arise although this should be checked numerically in some specific examples. We propose to do this in future work. The critical value Δ at which detonation failure occurs is given by

$$1 + (\gamma^2 - 1)\Delta_c \geq \left[1 + \frac{\gamma^2 - 1}{(C_1)^2} \sum_i \lambda_{is} q_i - (1+\gamma)\Delta\right]^2 \quad . \quad (67)$$

It would be interesting to explore ways in which this behavior could be checked with experiment. It should be noted that this theory predicts that the speed of deflagrations increases as the diameter decreases. At some critical diameter the detonation and deflagration velocities are the same and for smaller diameters there is no solution.

VI CONCLUSIONS AND RECOMMENDATIONS

The causes of nonideal behavior can be summarized in three categories.

(i) Incompletely effective use of the chemical energy for the detonation wave due to the nature of the chemical reactions. If there are reversible or endothermic reactions, the effects are especially important. For steady 1-dimensional flows the physical theory is prepared to handle the problem. The knowledge of the burning rates of the relevant chemical reactions, however, needs to be improved.

(ii) Loss of strength due to the lateral expansion of the explosive. Here the state of the physical theory is not so good. In Sec. V we presented a calculation for detonation failure. The radial flow was not calculated but was assumed known. The analytical solution presented should be checked with numerical calculations. A further step would be to compare these results with experiment. The author would like to be able to pursue these further developments.

(iii) Loss of strength due to transverse structure of the front and non-steady phenomena in the detonation. These effects are interesting per se and their effects on nonideal behavior are judged to be important[6]. These wave instability problems were not addressed in this research effort because the author felt he needed a good understanding of the simpler aspects of nonideal behavior before addressing them. There is much room for research into these effects using the techniques of nonlinear stability analysis and bifurcation theory.

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FINAL REPORT

CEPSTRUM ANALYSIS TECHNIQUES FOR POSSIBLE APPLICATION TO SEISMIC/ACOUSTIC RANGING

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CEPSTRUM ANALYSIS TECHNIQUES FOR POSSIBLE APPLICATIONS TO SEISMIC/ACOUSTIC RANGING

by

Franklin M. Ingels

ABSTRACT

The use of mines implanted by airdrop for target location, identification and destruction is a topic of current interest in the Air Force. The sensors for such mines must be capable of locating and identifying the target, but must also be capable of deciding whether the target is within range.

Multiple sensors may be used to determine the range, however, the geometry of emplacement, a factor which is critical to the range calculation, is difficult to control when implanting from the air. Using one sensor, it is possible to determine range if two signals are received which arrive from different modes of propagation. One is also faced with the signal processing algorithm if one sensor is used, since the two signals are in essence summed together.

Cepstral analysis offers the potential to determine the differences in time of arrival of two signals detected with the same sensor.

This report describes cepstral analysis, illustrates some results obtained for various synthetic signals, and comments on the limitations and possible applications of cepstral analysis for the ranging problem.

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Praises for the "Unsung Hero" award go to Karen Rife who put up with me through the summer and graciously types this report.

I. OBJECTIVES OF SUMMER RESEARCH EFFORT

Location and identification of targets through seismic/acoustic signal analysis is a topic of current interest in the Air Force TAMs program. Identification is accomplished mainly by using feature analysis (which may use simple to very complex algorithms) usually in the frequency domain. Location consists of two aspects. One is the angle to the target, the other is the range to the target. Ranging is presently accomplished through use of doppler techniques or by using multiple sensors and performing cross correlation to determine the difference in time of arrival of components of the signal which travel at different velocities. One idea of prime interest is the desirability of using only one sensor to detect both seismic and acoustic waveforms and to determine the range by acquiring the difference between arrival times of the two signals. However the signals from a single sensor are summed together and typically will not be separable by normal filtering techniques.

Cepstrum analysis which is a subclass of Homomorphic Deconvolution techniques is a method that can effectively separate these functions. Rather than separate the functions, however, it is satisfactory to determine the difference in time arrival of the two signals. This is a direct outcome of cepstrum analysis and, hence, it appears very attractive to pursue cepstrum techniques to determine range from single sensor signals.

The objectives of the summer research were to become familiar with the published literature concerning cepstrum analysis, to become familiar with the technique itself and to test the technique on synthesized data signals and on data tapes of digitized signals obtained through field measurements. With the exception of the last objective, all items were accomplished.

A cepstrum was computed for broadband noise measured in the field and is illustrated in Figure 17. The results of the summer effort indicate that cepstral analysis may be very useful in single sensor range determination. However, as is pointed out in the literature and as we experienced, Cepstrum results are data dependent.

Much work remains to derive optimum cepstral techniques for the type of signals in which we are interested. Recommendations for the initiation of this follow-on research are made in the last section of this report.

Two interesting points uncovered this summer were the limitations of FFT algorithms when dealing with power signals and a method whereby the cepstrum of a signal is greatly enhanced by frequency domain filtering to remove the major continuous signal components.

II. RESEARCH APPROACH AND RESULTS

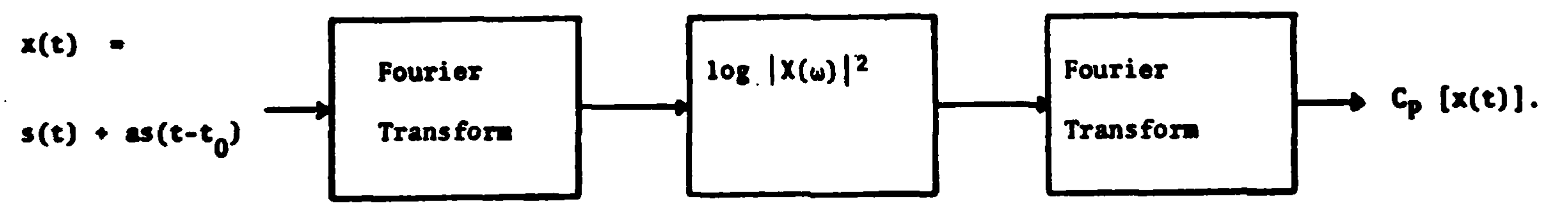
A possible situation that might arise is that of multiple targets of the same type within listening range or multi-path propagation of a single target signal. In either case, the received signal is a composite of the individual signals or of the multi-path signals. If the targets are of the same type (in the case of multiple targets) then it is very likely that the received signals are very similar in nature and will not be separable by normal filtering techniques nor by phase-slope calculations of the composite Fourier transform. In fact, a normal filtering approach or phase-slope technique will not detect the presence of multiple signals.

Cepstrum calculations will yield a definite indication of the presence of multiple signals and, if desired, may be used to eliminate one of the signals (i.e., the smaller of the set, or one could keep the largest signal in the case of more than two signals, allowing the location of one of the multiple targets).

There are two methods currently used to calculate cepstrum information:

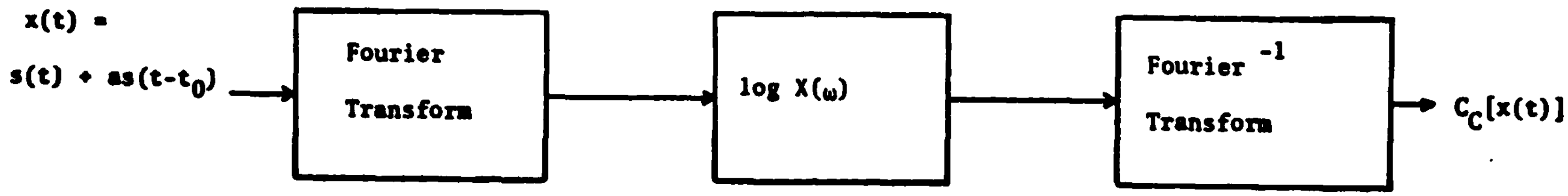
1. Power Cepstrum
2. Complex Cepstrum

Figure la illustrates the operations necessary to calculate the power cepstrum which is based upon the power spectrum. Figure lb illustrates the operations necessary to calculate the complex cepstrum. The complex cepstrum carries magnitude and phase information with it, whereas the power cepstrum deals only with the magnitude of the signal spectra. It has been determined that the power cepstrum is mose efficient in determining



$$C_p\ [x(t)] = F[\log |Fx(t)|^2] = \text{power cepstrum}$$

Figure 1a. Power Cepstrum



$$C_C\,[x(t)] = F^{-1}\,[\log\,[Fx(t)]\,] = \text{Complex cepstrum}$$

Figure 1b. Complex Cepstrum

different arrival times and amplitudes while the complex cepstrum is most valuable in estimating the main signal component.[1] Suppose we have an input to a sensor, a signal $s(t)$ plus a second signal $as(t-\tau)$. Then, we have

$$x(t) = s(t) + as(t-\tau)$$

and

$$\begin{aligned} F(x(t)) &= F(s(t)) + aF(s(t-\tau)) \\ &= F(s(t)) + aF(s(t))e^{-i\omega\tau} \\ &= F(s(t))\ [1 + ae^{-i\omega\tau}] \end{aligned}$$

where we will assume a is less than 1. (This does not hamper the real situation since we can always choose the larger of the signals to be $s(t)$ and if necessary multiply $x(t)$ by a suitable constant to normalize the problem.)

$$\log |F(x(t))|^2 = \log |F(s(t))|^2 + \log |1 + ae^{-i\omega\tau}|^2$$

but

$$\begin{aligned} |1 + ae^{-i\omega\tau}|^2 &= |1 + a\cos\omega\tau - ia\sin\omega\tau|^2 \\ &= ([(1 + a\cos\omega\tau)^2 + (a\sin\omega\tau)^2]^{1/2})^2 \\ &= (1 + a^2 + 2a\cos\omega\tau) \end{aligned}$$

Hence, we have

$$C_p(x(t)) = F[\log |F(s(t))|^2] + F[\log (1 + a^2 + 2a\cos\omega\tau)]$$

as the power cepstrum.

The first term is due to the input signal and the second term is due to the time-delayed amplitude-scaled signal and is a function of the scale factor a and the delay factor τ.

Examining the term $\log\,(1 + a^2 + 2a\cos\omega\tau)$, we have

$$\log\,(1 + a^2 + 2a\cos\omega\tau) = \log\,|1 + ae^{-i\omega\tau}|^2$$

$$= 2\,\log\,(1 + ae^{-i\omega\tau})$$

if a is less than 1.

$$\log\,(1+x) = \frac{\log_e(1+x)}{\log_e 10} = \frac{\sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n}\, x^n}{2.302585}$$

hence

$$F(\log\,|1 + ae^{-i\omega\tau}|^2) = 2\int_{-\infty}^{\infty} \log\,|1 + ae^{-i\omega\tau}|\, e^{j2\pi ft}\, df$$

$$= \frac{2}{2.302585}\int_{-\infty}^{\infty}\left(\sum_{n=1}^{\infty} (-1)^{n+1}\,\frac{1}{n}\,ae^{-i\omega\tau\, n}\right)e^{j2\pi ft}\, df$$

$$= .86858896 \sum_{n+1}^{\infty}\left(\frac{-1}{n}\right)a^n \int_{-\infty}^{\infty} e^{-in\omega\tau}\, e^{i2\pi ft} df$$

$$= .86858896 \sum_{n=1}^{\infty} \frac{(-1)^{n+1}\, a^n}{n}\,\delta(t-n\tau)$$

Thus the power cepstrum is

$$C_p(x(t)) = F[\log|F(s(t))|^2] + .86858896 \sum_{n=1}^{\infty} \frac{(-1)^{n+1}\, a^n}{n}\,\delta(t-n\tau).$$

Finally, we note that if we band limit the cepstrum by low pass filtering to eliminate the impulses while passing the low frequency cepstrum signal due to $2(\log A^2/4)\cos\omega\tau$, we then have the cepstrum due to the original signal only. Fourier transforming this will yield the power spectrum for the original signal sans echo. This technique, however, is not generally applicable since a cepstrum with frequency content that requires a significant filter bandwidth would also allow some of the impulse energy through. A preferable technique would be to identify the impulses and use a notch time filter to block them out by forcing the cepstrum to zero at these points (or to an appropriate value).

Extending the cepstrum discussion to more than one echo or multi-path signal is not difficult. Suppose

$$x(t) = x_1(t) + x_2(t) + x_3(t)$$

$$= A\cos\omega_2 t + B\cos\omega_1(t-\tau_1) + C\cos\omega_1(t-\tau_2)$$

then

$$F[x(t)] = \frac{A}{2}\delta(f-f_1) + \frac{A}{2}\delta(f+f_1) + \frac{B}{2}\delta(f-f_1)e^{-j\omega\tau_1}$$

$$+ \frac{B}{2}\delta(f+f_1)e^{-j\omega\tau_1} + \frac{C}{2}\delta(f-f_1)e^{-j\omega\tau_2}$$

$$+ \frac{C}{2}\delta(f+f_1)e^{-j\omega\tau_2}$$

$$= \frac{A}{2}\delta(f-f_1) + \frac{B}{2}\delta(f-f_1)e^{-j\omega\tau_1} + \frac{C}{2}\delta(f-f_1)e^{-j\omega\tau_2} + \frac{A}{2}\delta(f+f_1)$$

$$+ \frac{B}{2}\delta(f+f_1)e^{-j\omega\tau_1} + \frac{C}{2}\delta(f+f_1)e^{-j\omega\tau_2}$$

$$= \frac{A}{2}\,\delta(f-f_1)\left[1 + \frac{B}{A}e^{-j\omega\tau_1} + \frac{C}{A}e^{-j\omega\tau_2}\right] + \frac{A}{2}\,\delta(f+f_1)\left[1 + \frac{B}{A}e^{-j\omega\tau_1} + \frac{C}{A}e^{-j\omega\tau_2}\right]$$

or

$$F[x(t)] = \left[\frac{A}{2}\,\delta(f-f_1) + \frac{A}{2}\delta(f+f_1)\right]\left[1 + \frac{B}{A}e^{-j\omega\tau} + \frac{C}{A}e^{-j\omega\tau}\right]$$

The logarithmic amplitude of the power spectrum is thus

$$\mathrm{Log}\,|F(x(t))|^2 = \mathrm{Log}\left(\frac{A^2}{4}\,\delta(f-f_1) + \frac{A^2}{4}\,\delta(f+f_1)\right) + \mathrm{Log}\left|1 + \frac{B}{A}e^{-j\omega\tau_1} + \frac{C}{A}e^{-j\omega\tau_2}\right|^2$$

Investigating the second term

$$\mathrm{Log}\left|1 + \frac{B}{A}e^{-j\omega\tau_1} + \frac{C}{A}e^{-j\omega\tau_2}\right|^2 = 2\mathrm{Log}\left|\left(1 + \frac{B}{A}e^{-j\omega\tau_1} + \frac{C}{A}e^{-j\omega\tau_2}\right)\right|$$

letting $B/A = \alpha_1$ and $C/A = \alpha_2$, and again assuming $\alpha_1 < 1$ and $\alpha_2 < 1$, we have

$$= 2\mathrm{Log}\left|\left(1 + \alpha_1 e^{-j\omega\tau_1} + \alpha_2 e^{-j\omega\tau_2}\right)\right|$$

This expression is not as clearly handled as the case for one echo.

If τ_2 is a multiple of τ_1, then the cepstrum will have impulses that lie in the same place on the time axis as for the single echo but whose amplitude will vary in a different manner.

In general, if the echoes (or multi-path signals) are not equally spaced, then the cepstrum will consist of impulses that occur at times that are complicated functions of the original arrival times. If the sequence of arriving pulses may be described by a mathematical sequence that is minimum phase then R. W. Schafer has shown in a dissertation (MIT, Feb 1968) that the cepstrum will consist of impulses occuring at multiples of the different arrival times.

By using exponential weighting, a nonminimum phase sequence can be made minimum phase, hence, the general case can be forced to the minimum phase result.

One other comment is worth noting. If we determine the peak value of the signal (A), then by normalizing A to 4 units, we may force the term in the cepstrum to zero and the resulting plot will be due to the echoes only. A word of caution is in order, however, The above analysis presumes the starting times of the individual components of the waveform is at $t = -\infty$ seconds. That is, the signals are assumed to have past history and the fourier transform is assumed to be determined over the inverval $-\infty \leq t \leq \infty$

If we consider the FFT that would be utilized to perform the fourier transform, then the starting times of the signals are not at $t = -\infty$, but at $t = 0$, which is the time of initiation of the transform.

The following analysis for a continuous signal pair which have different starting times as well as different phases will illustrate the problem that arises. Figure 2 illustrates the waveform pair while Figures 3 through 12 illustrate the results as $\infty \to 0$.

A mathematics model for the continuous signal case follows. Assume we have a generalized situation (see Figure 2)

$$e(t) = A\sin(\omega_0 t)u(t) + B\Big(\sin\omega_0(t-\tau)\Big)u(t-\gamma).$$

$$F(e(t)) = F\Big(A\sin(\omega_0 t)u(t)\Big) + F\Big(B(\sin\omega_0(t-\tau))u(t-\gamma)\Big)$$

$$F\Big((A\sin\omega_0 t)u(t)\Big) = \int_0^\infty A\sin\omega_0 t\; e^{-j\omega\tau}\, dt$$

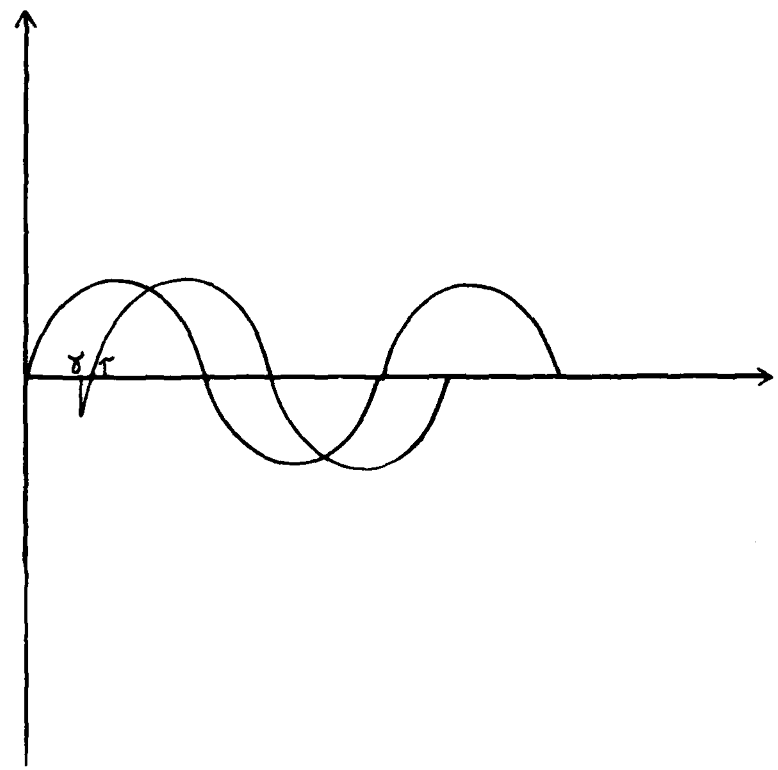


FIGURE 2. COMPOSITE SIGNAL EQUALS SUM OF SIGNALS SHOWN

$$= A\int_0^\infty \frac{e^{-j\omega_0\tau} - e^{-j\omega_0\tau}}{2j} \quad e^{-j\omega\tau} \quad dt$$

$$= \frac{A}{2j}\left[\frac{e^{-j(\omega-\omega_0)t}}{-j(\omega-\omega_0)}\right]_{t=0}^{\infty} - \left[\frac{A}{2j} \quad \frac{e^{-j(\omega+\omega_0)t}}{-j(\omega+\omega_0)}\right]_{t=0}^{\infty}$$

$$= \frac{-\omega_0 A}{\omega^2-\omega_0{}^2}$$

$$F(B\sin\omega_0(t-\tau)u(t-\gamma)) = \int_\gamma^\infty B\sin\omega_0(t-\tau)e^{-j\omega t}\,dt$$

$$= B\int_\gamma^\infty \frac{e^{j\omega_0(t-\tau)} - e^{-j\omega_0(t-\tau)}}{2j} \quad e^{-j\omega t} \quad dt$$

$$= \frac{B}{2j}\int_\gamma^\infty \left(e^{j\omega_0 t} \; e^{-j\omega t} \; e^{-j\omega_0\tau} - e^{-j\omega_0 t} \; e^{j\omega_0\tau} \; e^{-j\omega t}\right)dt$$

$$= \frac{B}{2j}\int_\gamma^\infty e^{-j(\omega-\omega_0)t} \; e^{-j\omega_0\tau}dt - \frac{B}{2j}\int_\gamma^\infty e^{-j(\omega+\omega_0)t} \; e^{j\omega_0\tau} \; dt$$

$$= \frac{Be^{-j\omega_0\tau}}{2j}\int_\gamma^\infty e^{-j(\omega-\omega_0)t} \; dt - \frac{Be^{j\omega_0\tau}}{2j}\int_\gamma^\infty e^{-j(\omega+\omega_0)t} \; dt$$

$$= \frac{Be^{-j\omega_0\tau}}{2j}\left(\frac{e^{-j(\omega-\omega_0)\gamma}}{j(\omega-\omega_0)}\right) - \frac{Be^{j\omega_0\tau}}{2j}\left(\frac{e^{-j(\omega+\omega_0)\gamma}}{j(\omega+\omega_0)}\right)$$

$$= \frac{Be^{-j\omega\gamma}}{2j^2}\left(\frac{e^{j\omega_0\gamma}e^{-j\omega_0\tau}}{\omega-\omega_0} - \frac{e^{-j\omega_0\gamma}e^{j\omega_0\tau}}{\omega+\omega_0}\right)$$

$$= \frac{-Be^{-j\omega\gamma}}{2}\left(\frac{e^{-j\omega_0(\tau-\gamma)}}{\omega-\omega_0} - \frac{e^{j\omega_0(\tau-\gamma)}}{\omega+\omega_0}\right)$$

$$= \frac{-Be^{-j\omega\gamma}}{2}\left(\frac{e^{-j\omega_0(\tau-\gamma)}(\omega+\omega_0) - e^{\omega_0(\tau-\gamma)}(\omega-\omega_0)}{\omega^2-\omega_0^2}\right)$$

$$= \frac{-Be^{-j\omega\gamma}}{2}\left(\frac{\omega(e^{j\omega_0(\gamma-\tau)} - e^{-j\omega_0(\gamma-\tau)}) + \omega_0(e^{j\omega_0(\gamma-\tau)} + e^{-j\omega_0(\gamma-\tau)})}{\omega^2 - \omega_0^2}\right)$$

$$= -Be^{-j\omega\gamma}\left(\frac{\omega_0}{\omega^2-\omega_0^2}\, j\sin\omega_0(\gamma-\tau) + \frac{\omega_0}{\omega^2-\omega_0^2}\cos\omega_0(\gamma-\tau)\right)$$

$$\frac{-Be^{-j\omega\gamma}}{\omega^2-\omega_0^2}\left(\omega_0\cos\omega_0(\gamma-\tau) + j\omega\sin\omega_0(\gamma-\tau)\right)$$

Thus we have for F(e(t))

$$F(e(t)) = \frac{-\omega_0 A - B\omega_0\cos\omega_0(\gamma-\tau)e^{-j\omega\gamma} - jB\omega\sin\omega_0(\gamma-\tau)e^{-j\omega\gamma}}{\omega^2 - \omega_0^2}$$

$$|F(e(t))|^2 = \frac{\omega_0^2A^2+2\omega_0^2AB\cos\omega_0(\gamma-\tau)e^{-j\omega\gamma}+B^2\omega_0^2\cos^2\omega_0(\gamma-\tau)e^{-j2\omega\gamma}+B^2\omega^2\sin^2\omega_0(\gamma-\tau)e^{-j2\omega\gamma}}{(\omega^2 - \omega_0^2)^2}$$

$$= \frac{\omega_0{}^2A^2+2\omega_0{}^2AB\cos\omega_0(\gamma-\tau)e^{-j\omega\gamma}+B^2(\omega_0{}^2\cos^2\omega_0(\gamma-\tau)-\omega^2\sin^2\omega_0(\gamma-\tau)e^{-j2\omega\gamma}}{(\omega^2 \quad \omega_0{}^2)^2}$$

$$= \frac{\omega_0{}^2A^2}{(\omega^2+\omega_0{}^2)} \quad 1 + 2\frac{B}{A}\cos\omega_0(\gamma-\tau)e^{-j\omega\gamma} + \frac{B^2}{\omega_0{}^2A^2}(\omega_0{}^2\cos^2\omega_0(\gamma-\tau) + \quad \sin\omega_0(\gamma-\tau)e^{-j2\omega\gamma}$$

$$\text{Log } |Fe(t)|^2 = \text{Log } \frac{\omega_0{}^2 \; {}^2}{(\omega^2+\omega_0{}^2)^2} + \text{Log }(1 + a_1e^{-j\omega\gamma} + a_2e^{-j2\omega\gamma} + \quad a_3e^{-j2\omega\gamma})$$

$$a_1 = 2\frac{B}{A}\cos\omega_0(\gamma-\tau); \; a_2 = \frac{B^2\cos^2\omega_0(\gamma-\tau)}{A^2}; \; a_3 = \frac{B^2\sin^2\omega_0(\gamma-\tau)}{\omega_0{}^2 \; A^2}$$

For the case $\gamma=\tau$, we have

$$\text{Log } |Fe(t)|^2 = \text{Log } \frac{\omega_0{}^2 \; A^2}{(\omega^2+\omega_0{}^2)} + \text{Log }\left(1 + 2\frac{B}{A} e^{-j\omega\tau} + \frac{B^2}{A^2}e^{-j2\omega\tau}\right)$$

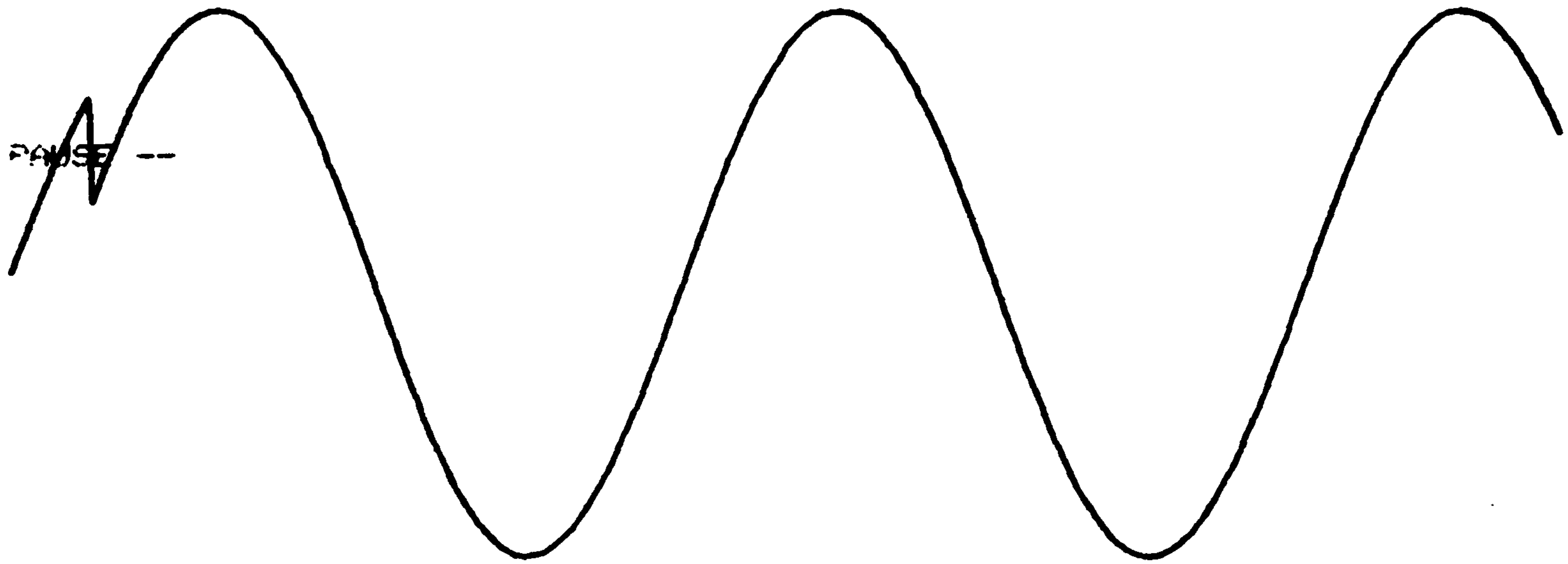
which, when the fourier transform is applied, will yield a train of impulses in time occuring at intervals τ.

This is confirmed by the plots in Figures 3 and 4 for which A = 10, B = 6, frequency = 10 Hz, the sample period is .25 second. For the case $\gamma \to 0$, we have

$$\text{Log } |Fe(t)|^2 = \text{Log } \frac{\omega_0{}^2A^2}{(\omega^2+\omega_0{}^2)^2} + \text{Log } \quad (1 + \frac{B}{A}\cos\omega_0\tau) + \frac{B^2\sin^2\omega_0\tau}{\omega_0{}^2A^2}\,\omega^2$$

$$= \text{Log } \frac{K_1}{(\omega^2+\omega_0{}^2)^2} + \text{Log } \; K_2(1 + K_3\omega^2)$$

$$= \text{Log } \frac{K_1}{(\omega^2+\omega_0{}^2)} + \text{Log } K_2 + \text{Log }(1 + K_3\omega^2)$$



SUM OF TWO SINE WAVES, $\gamma = \tau/2$, $\tau = .027$

FIGURE 3

CEPSTRUM FOR FIGURE 3. FIGURE 4.

where $K_1 = \omega_0{}^2A^2$; $K_2 = 1 = \frac{B}{A}\cos\omega_0\tau$; $K_3 = \dfrac{B^2\sin^2\omega_0\tau}{\omega_0{}^2A^2(1+\frac{B}{A}\cos\omega_0\tau)}$

This form will not produce any impulse train in the spectral plot for Log $|Fe(t)|^2$.

In Figures 5 through 12, we see the tendancy as $\gamma \rightarrow 0$ for the impulses to colocate at the origin. There is no information term in the expression which would yield information concerning τ, if $\gamma \rightarrow 0$. Thus we see the cepstrum is not a viable technique for continuous signals which differ only in phase angle. An experimental test set-up as shown in Figure 13 was monitored and the signals from the microphone-geophone pair indicated were added together as if detected by a single sensor.

The resulting signal is indicated in Figure 14 for an input of broadband noise to the speaker. The magnitude of the FFT, Figure 15, illustrates a strong energy distribution over the frequency range of 32 to 64 Hertz. The logarithm spectrum, Figure 16, illustrates a definite ripple which is illustrated as a peak at 72 milliseconds in the cepstrum plot of Figure 17. This delay, 72 milliseconds, is approximately the time difference in arrival of the acoustic energy and the seismic energy. (The acoustic velocity is approximately 1120 feet per second and the seismic velocity for this soil is approximately 400 feet per second.)

The equation for range calculation is given by

$$\text{Range} = T_d\left(\frac{V_aV_s}{V_a-V_s}\right).$$

Thus, for this example, we have a range calculation of

$$R = (72\text{x}10^{-3})\left(\frac{1120 \text{ x } 400}{1120 - 400}\right) = 44.8 \text{ feet}$$

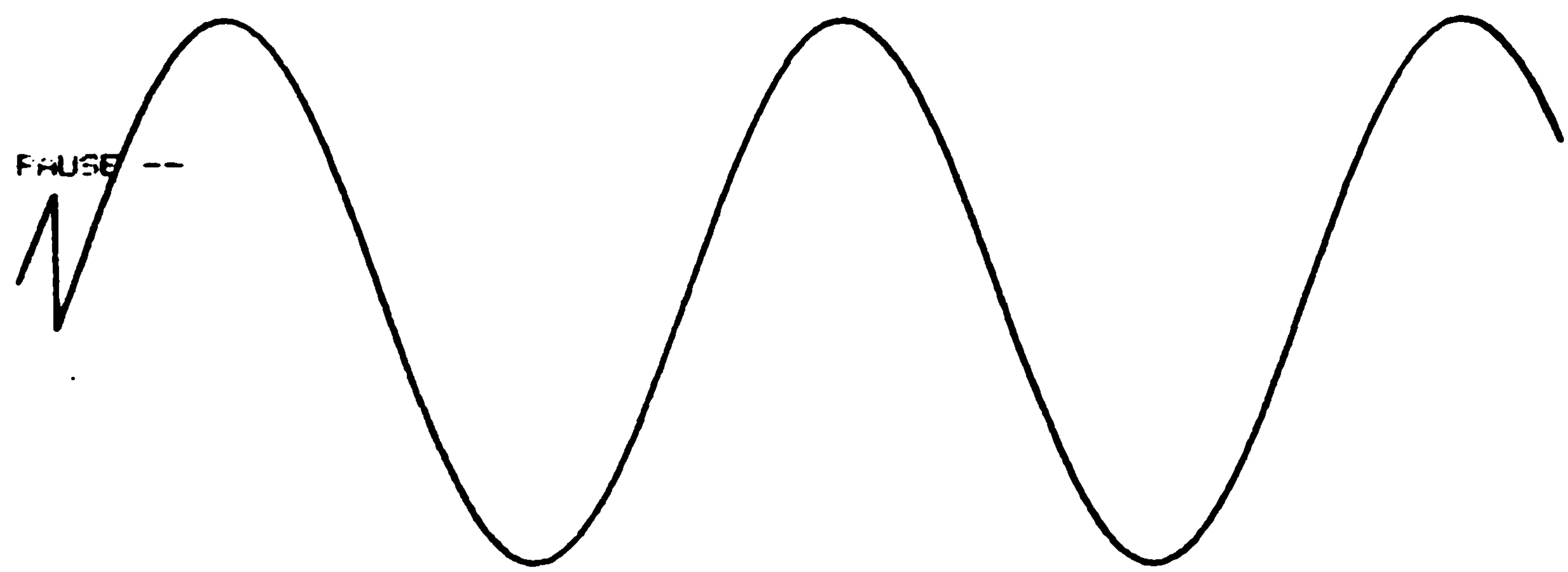


FIGURE 5. SUM OF TWO SINE WAVES, $\gamma = \tau/4$, $\tau = .027$

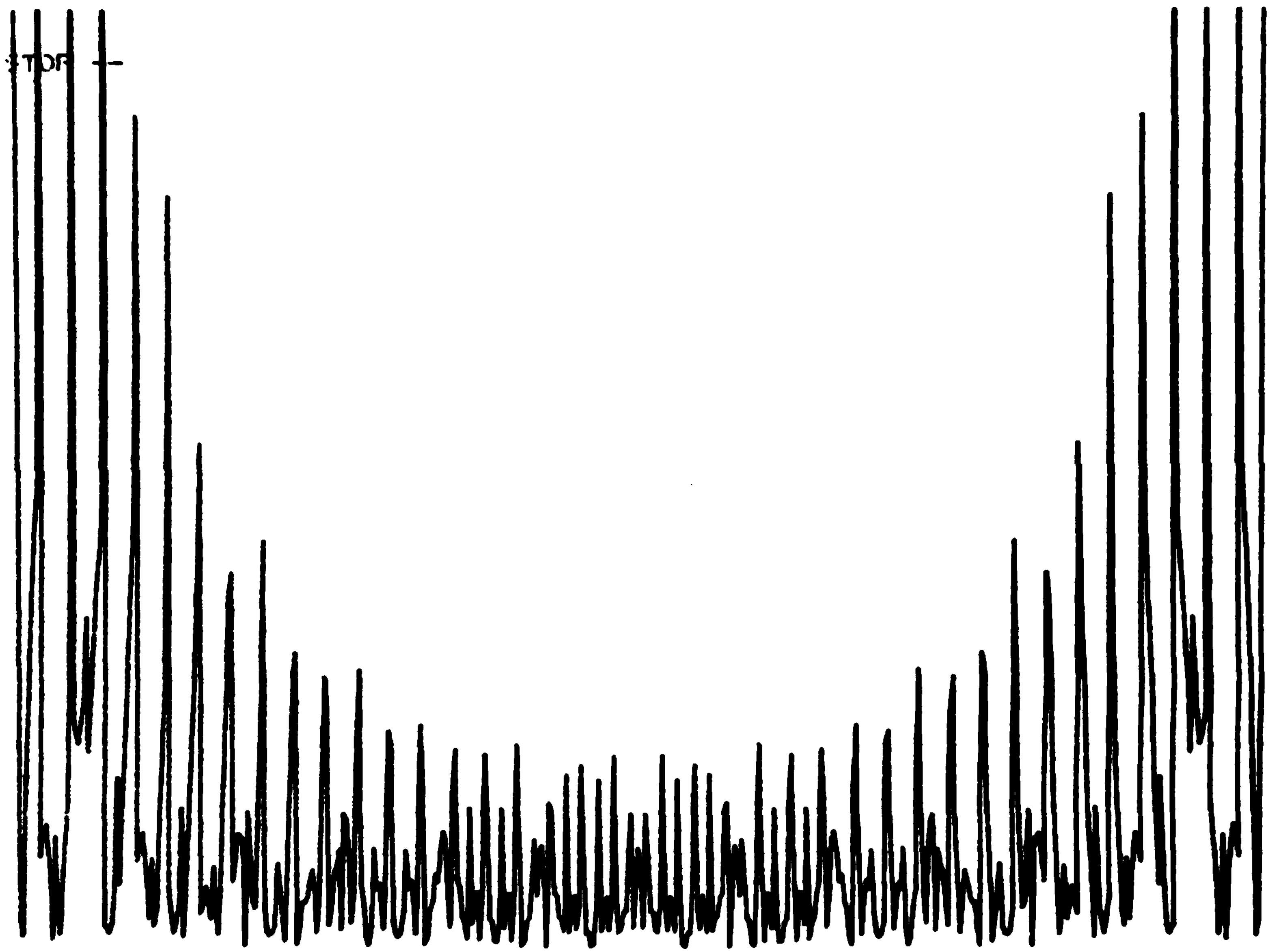


FIGURE 6. CEPSTRUM FOR FIGURE 5, $\gamma = \tau/4$

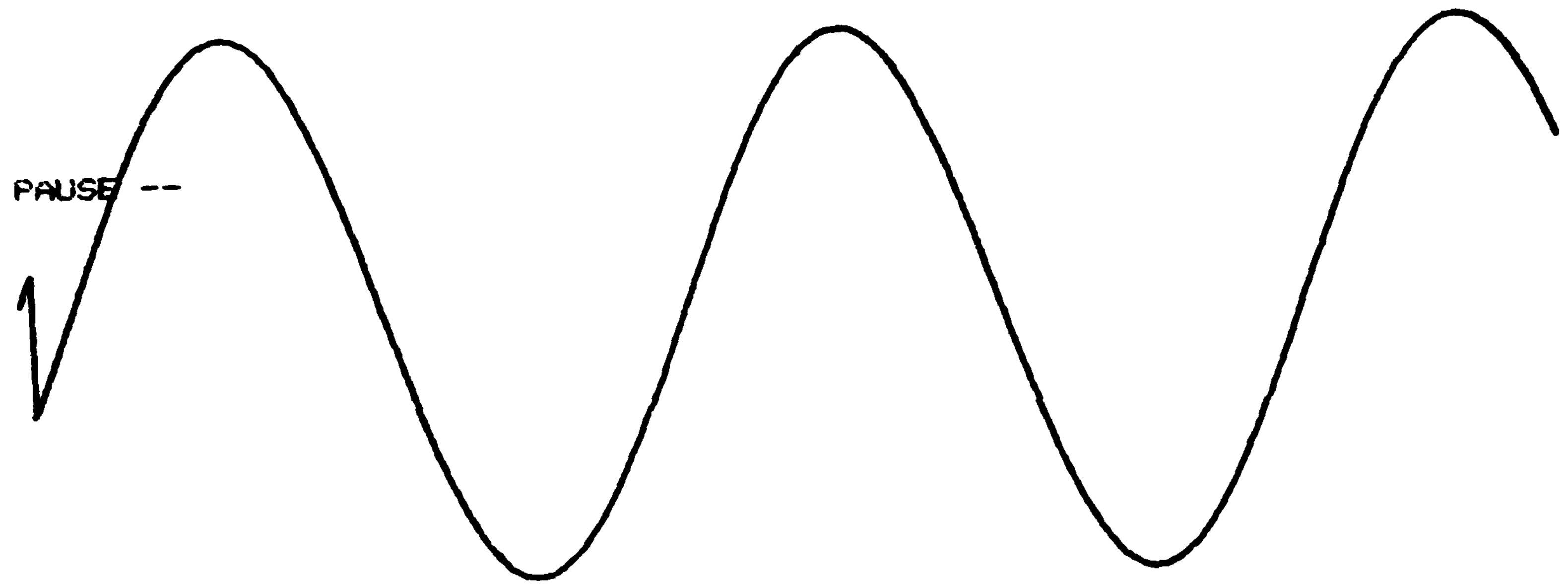


FIGURE 7. SUM OF TWO SINE WAVES, $\gamma = \tau/10$, $\tau = .027$

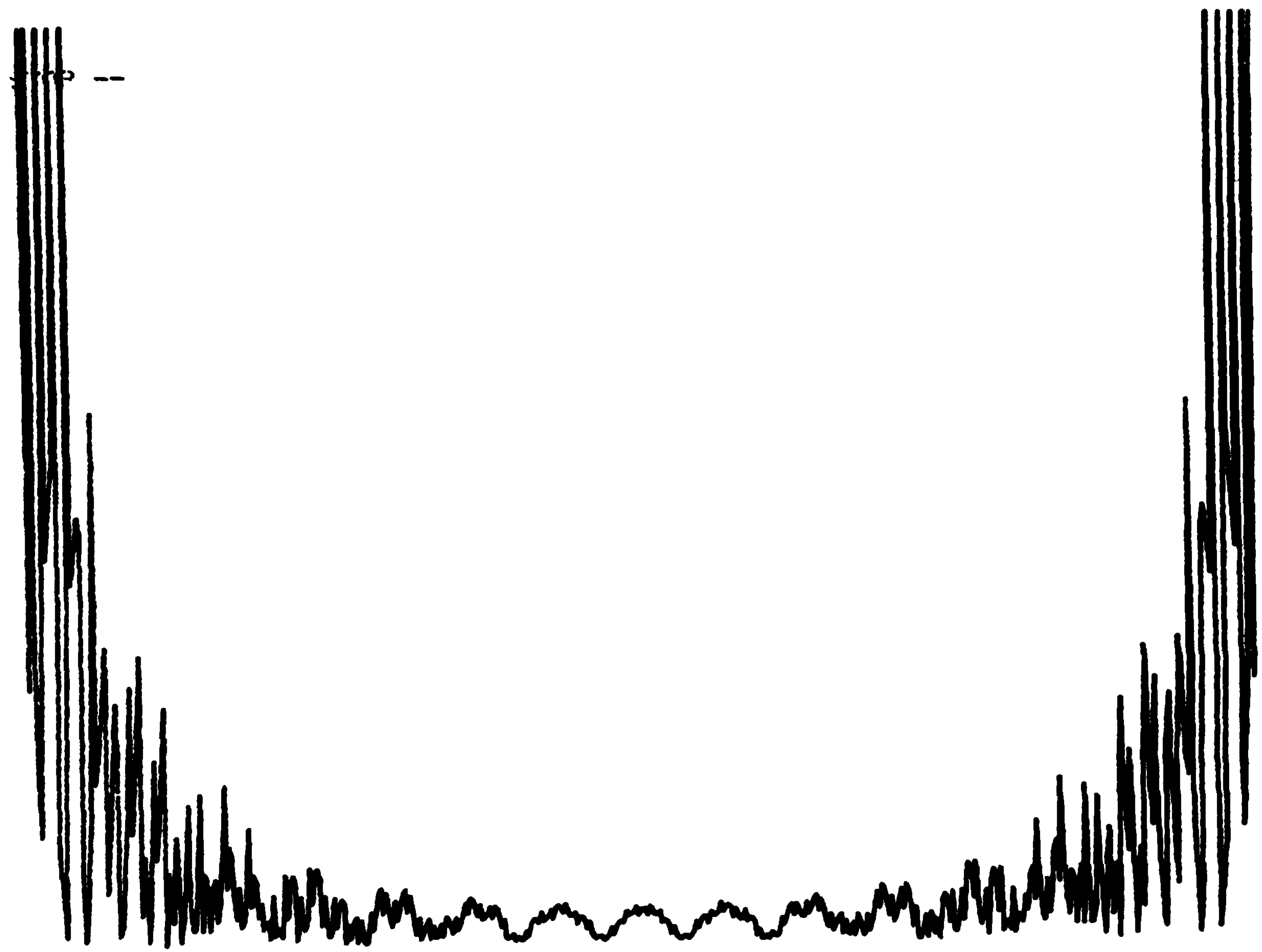


FIGURE 8. CEPSTRUM FOR FIGURE 7, $\gamma = \tau/10$

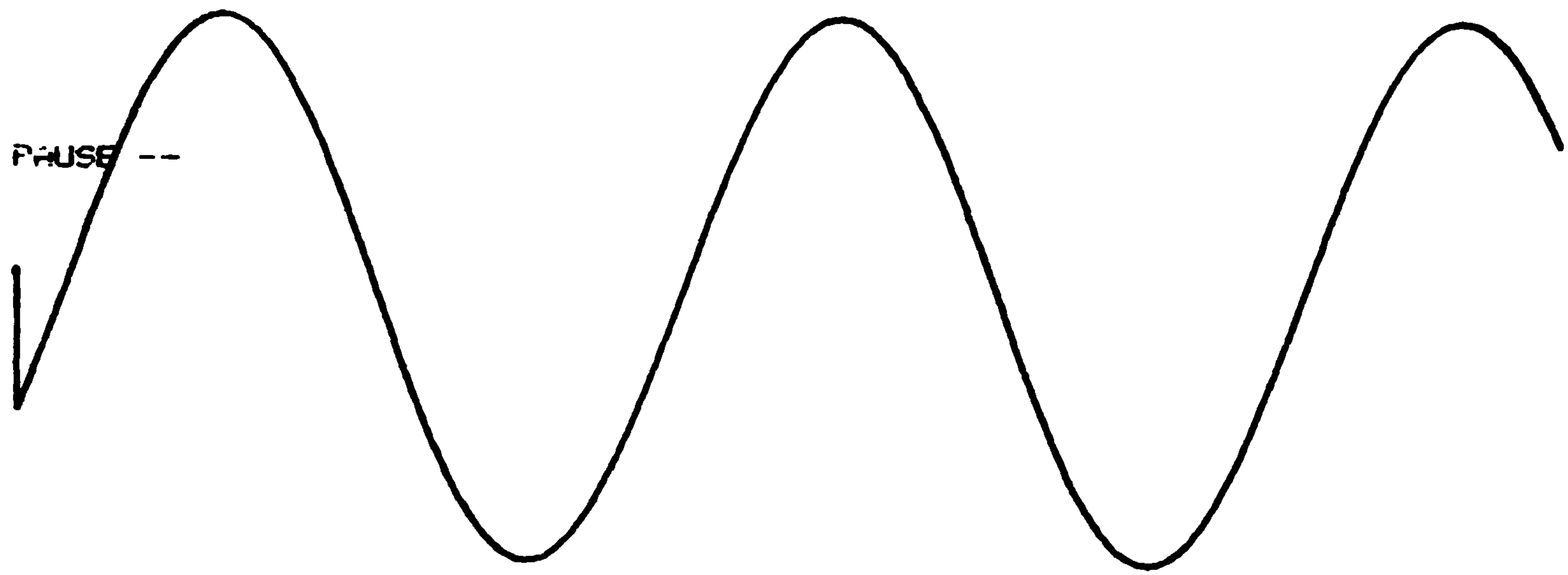


FIGURE 9. SUM OF TWO SINE WAVES, $\gamma = \tau/20$, $\tau = .027$

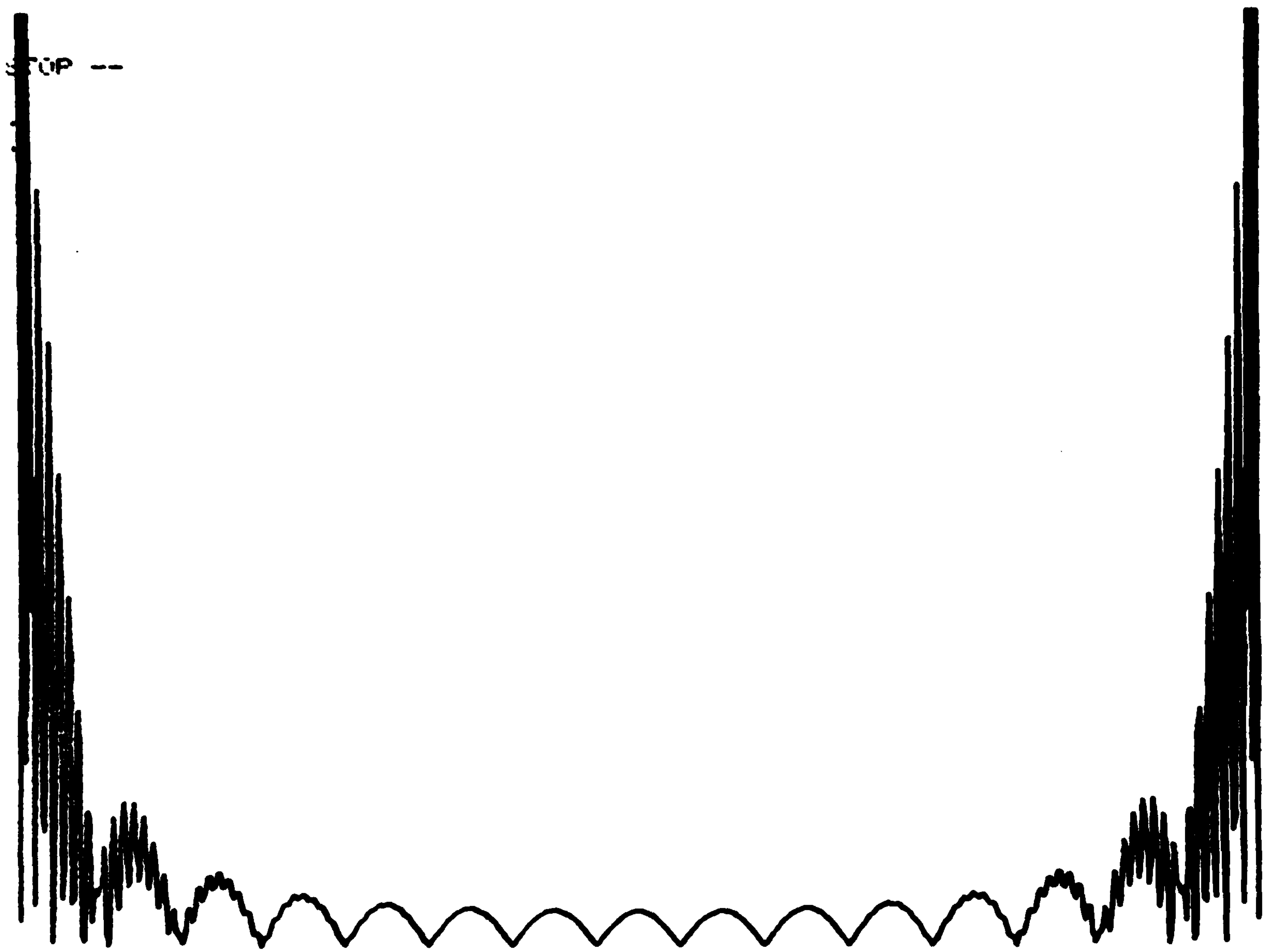


FIGURE 10. CEPSTRUM FOR FIGURE 9, $\gamma = \tau/20$

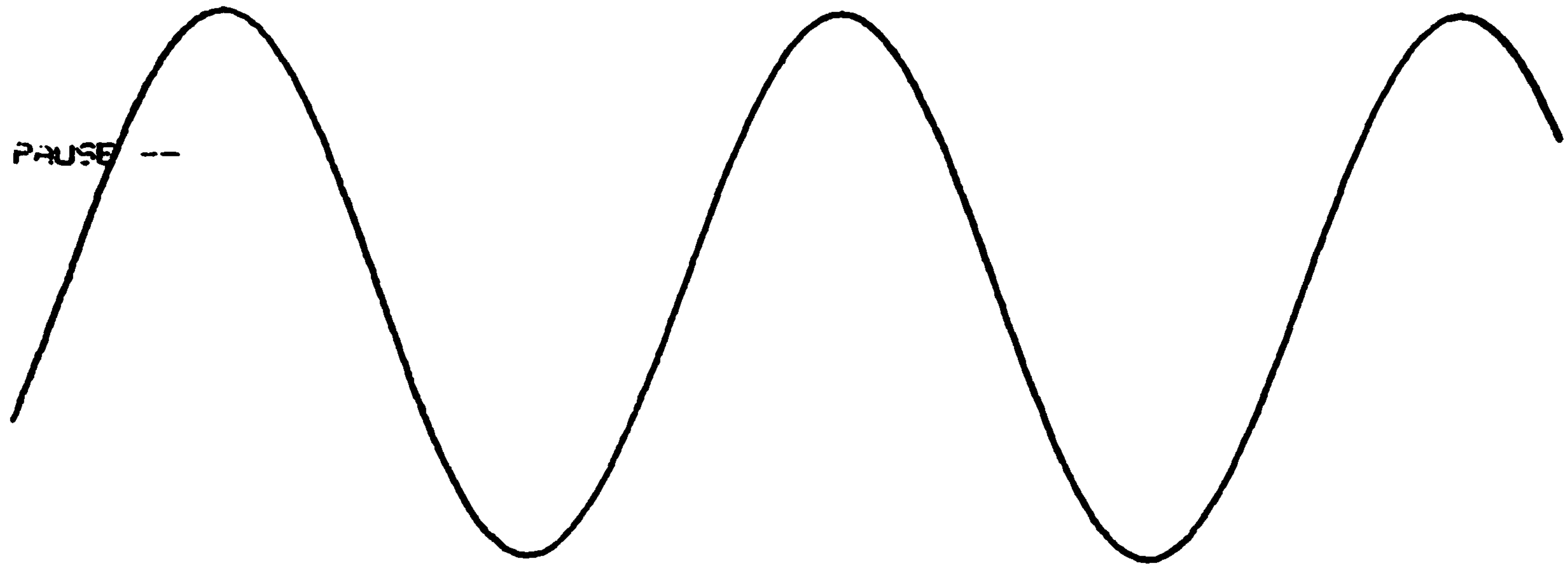


FIGURE 11. SUM OF TWO SINE WAVES, $\gamma = \tau/99$, $\tau = .027$

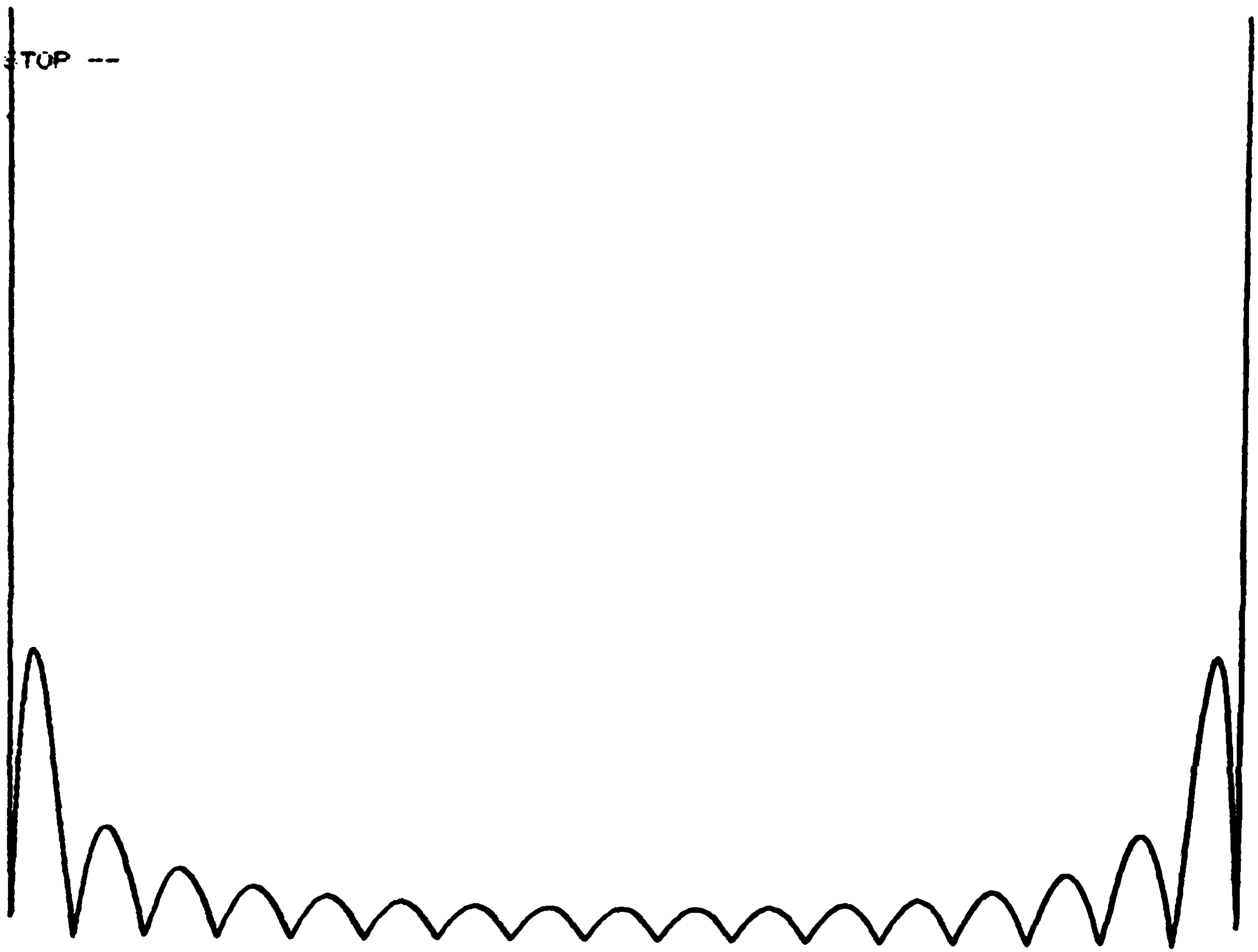


FIGURE 12. CEPSTRUM FOR FIGURE 11, $\gamma = \tau/99$

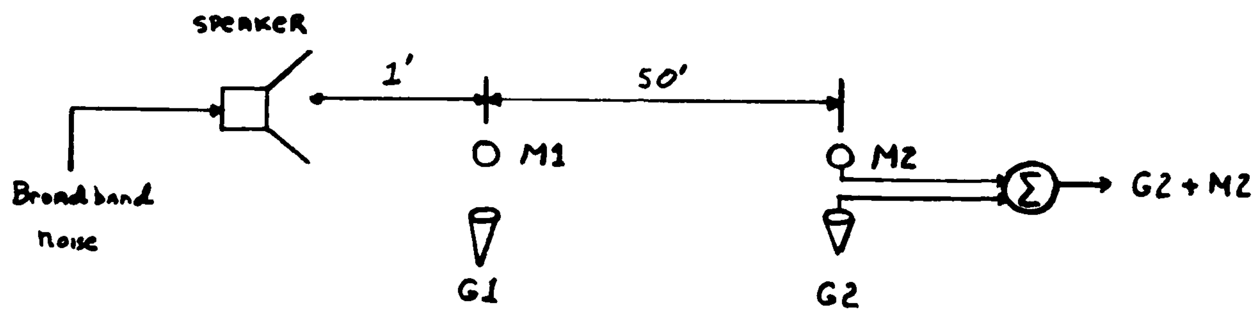


FIGURE 13. TEST SET-UP FOR BROADBAND NOISE

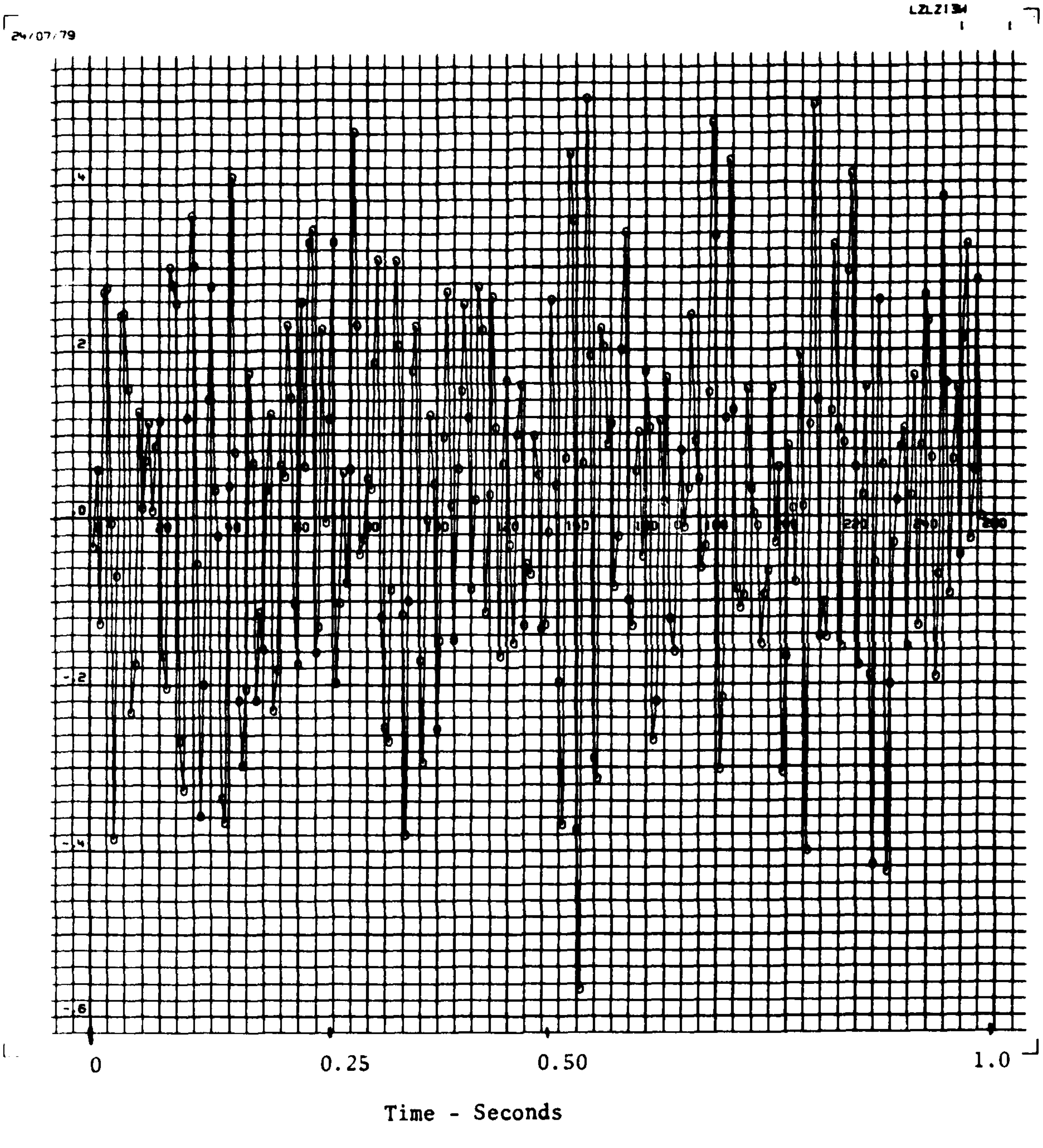


FIGURE 14. A BROADBAND NOISE SIGNAL FOR FIGURE 13.

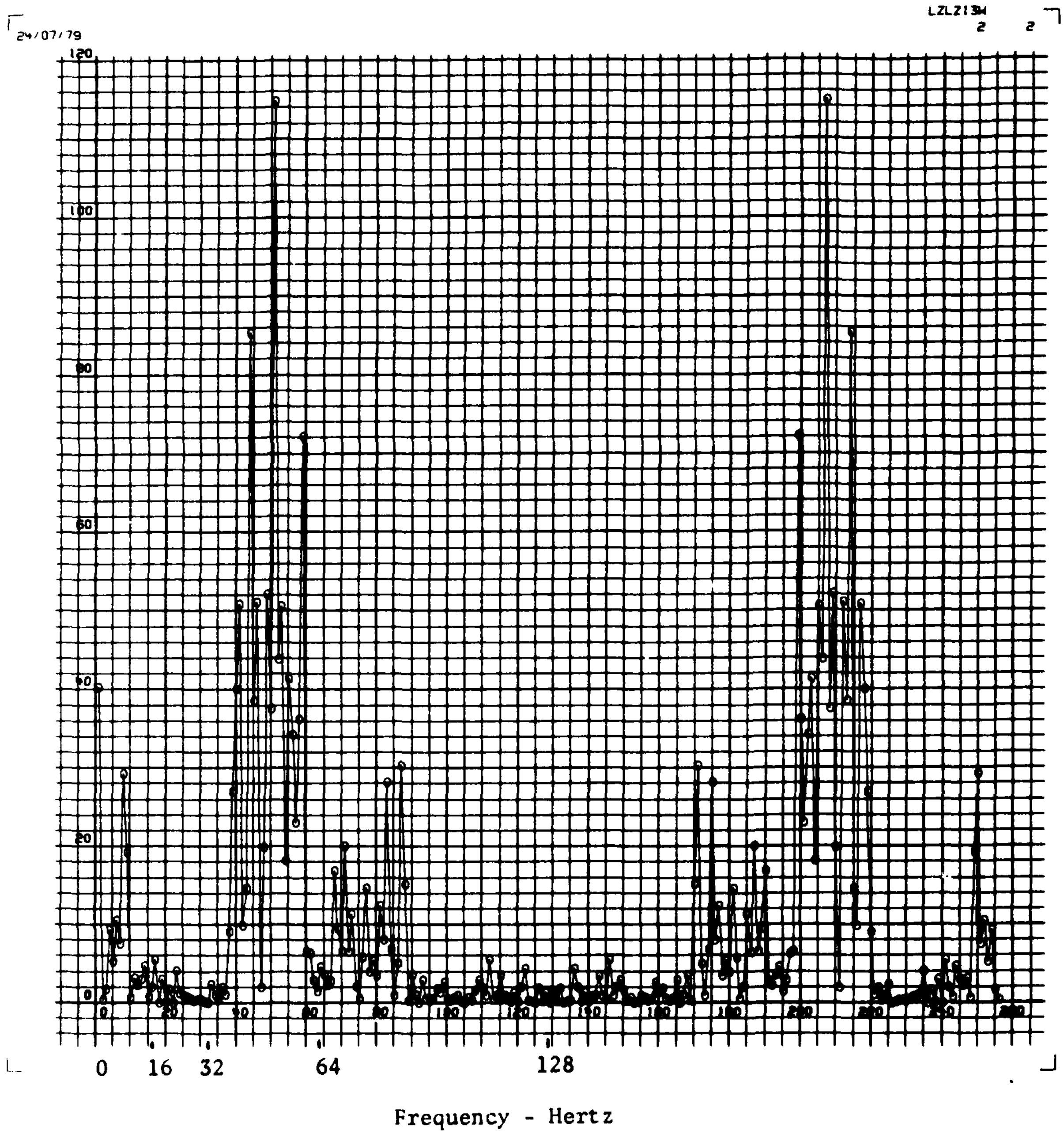
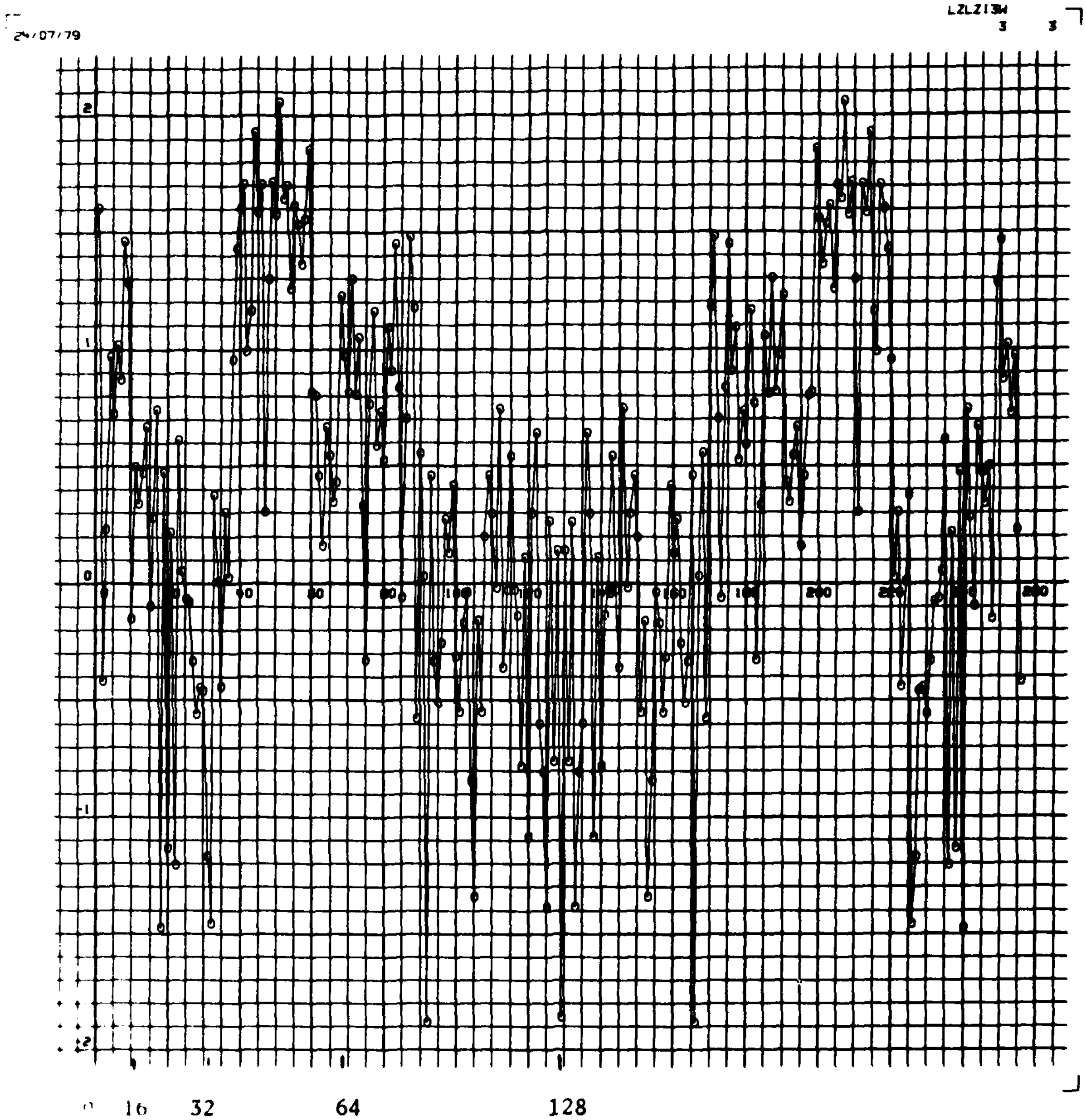


FIGURE 15. MAGNITUDE OF FFT FOR SIGNAL OF FIGURE 14.



Frequency - Hertz

FIGURE 16. LOGARITHM OF SPECTRUM OF FIGURE 15.

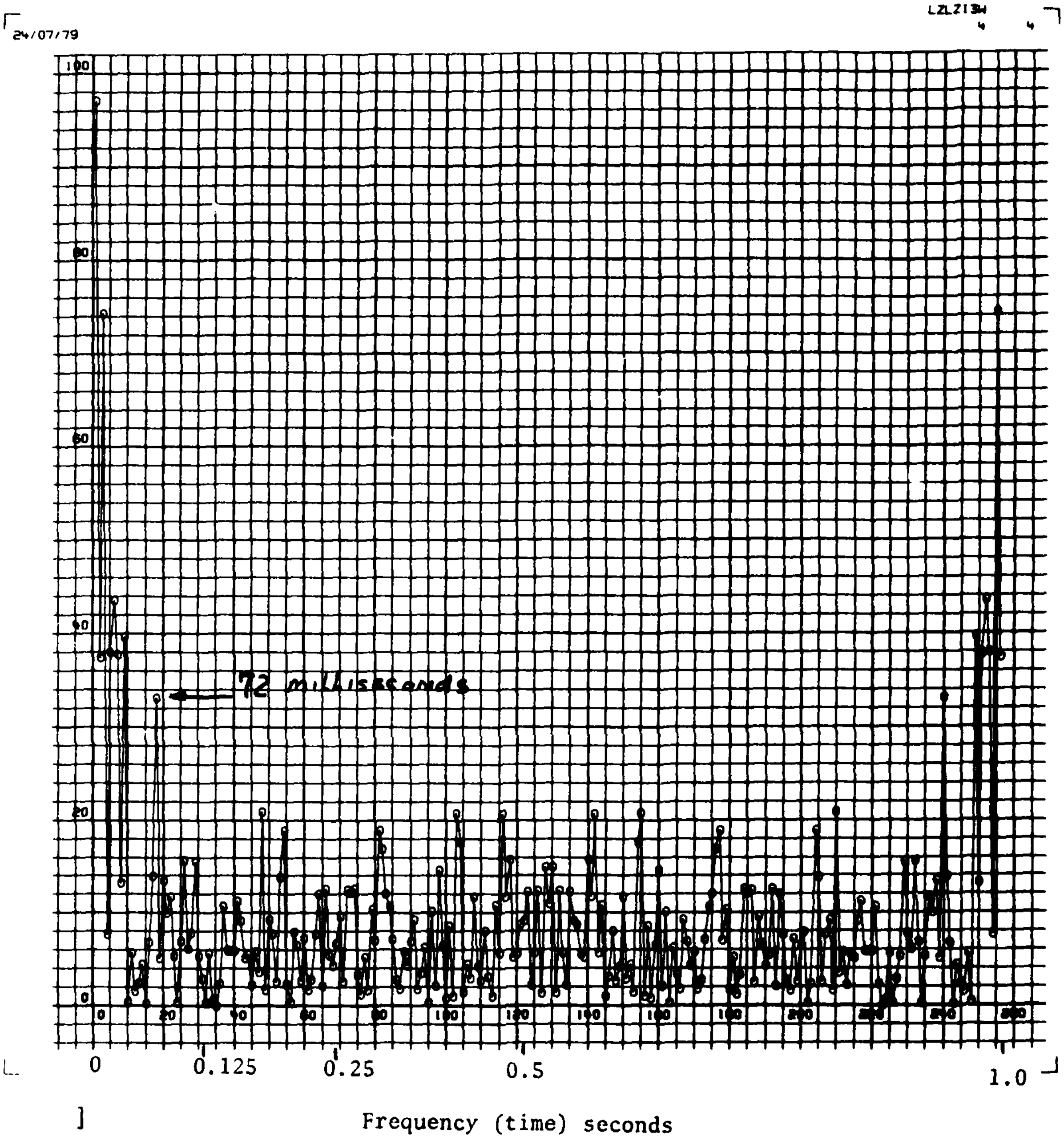


FIGURE 17. CEPSTRUM OF SIGNAL OF FIGURE 14.

Enhancement of the cepstral peak might be accomplished in several ways and algorithms which might be used to calculate range and disregard false echoes may be developed. One possible algorithm would be the use of head-to-shoulders threshold tests to pick out peaks within a distance range of 30 feet to 300 feet. By ignoring data in the first 30 milliseconds, the peaks due to windowing and to the special cepstrum of the basic signal may be ignored. The target must come into range from a far distance so it is not likely to miss a target by using a restrictive time gate.

Use of feature algorithms in the FFT data plus the cepstrum for range determination seems feasible to perform both target classification and ranging using a single sensor. (A promising sensor is the tube sensor being investigated by AFATL/DLJF, Eglin AFB FL).

Figure 18 illustrates the cross spectrum correlation plot for a signal e(t):

$$e(t) = \cos(200\pi t)u(t) + \cos(200\pi(t-\tau))u(t-\tau).$$

The time delay may be determined (with difficulty, however) from the ripple in the cross spectrum correlation. Correspondingly, a cepstrum was calculated, Figure 19, and the peak corresponding to the time delay, τ, is easily seen. In Figure 20 is a cepstrum plot which has been enhanced by selected filtering in the frequency domain to eliminate the continuous signal frequency of 100 hertz. The resulting improvement is obvious. In Figure 21, a cepstral plot for the sum of two signals detected by microphone 50 feet apart is illustrated. Using the peak at 44 milliseconds to calculate the range, we have

$$R = 1120 \text{ ft/sec} \times 44 \times 10^{-3} \text{ sec} = 49.28 \text{ ft}.$$

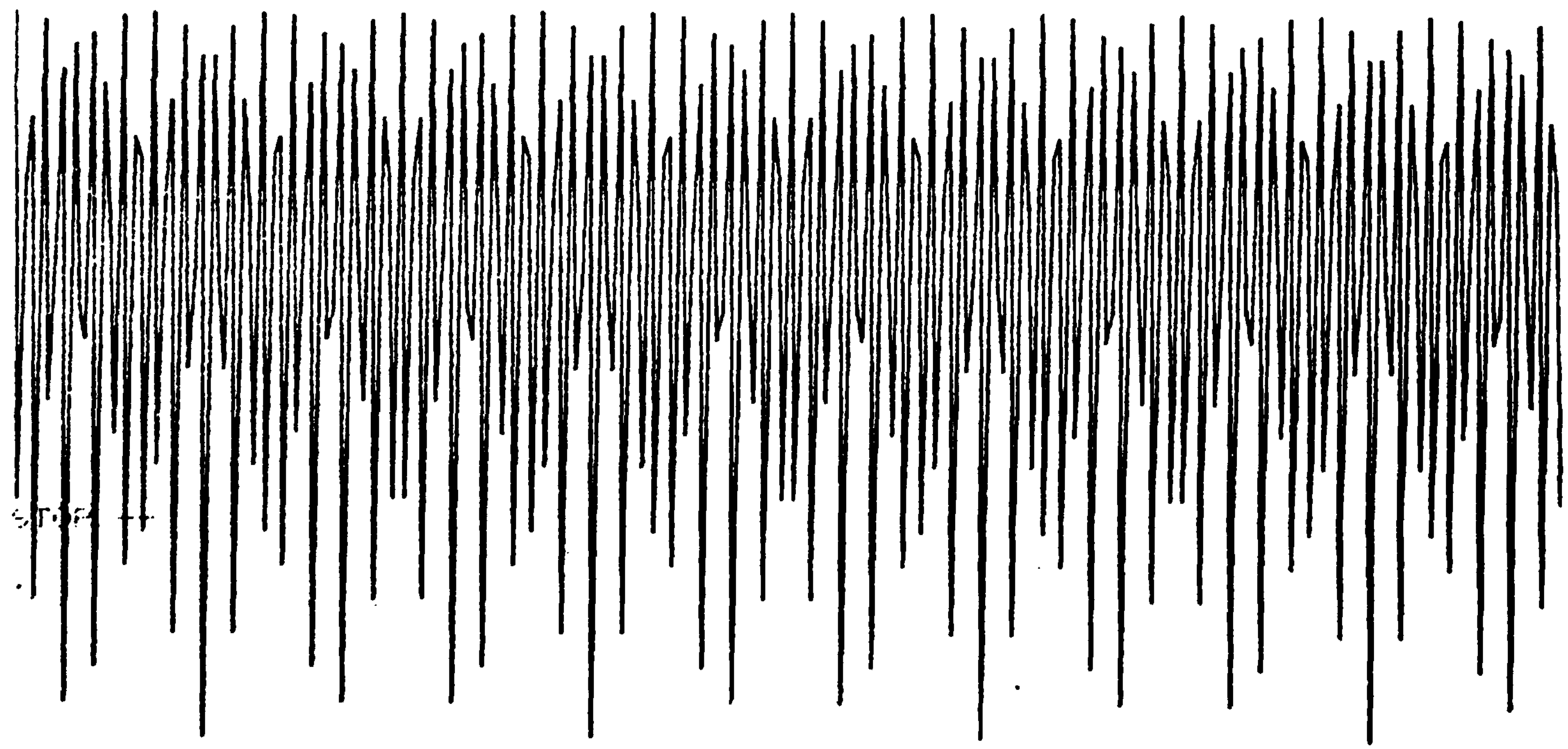


FIGURE 18. CROSS SPECTRUM CORRELATION PLOT FOR THE SIGNAL $e(t) = \cos(200\pi t)u(t) + \cos[200\pi(t-\tau)]u(t-\tau)$

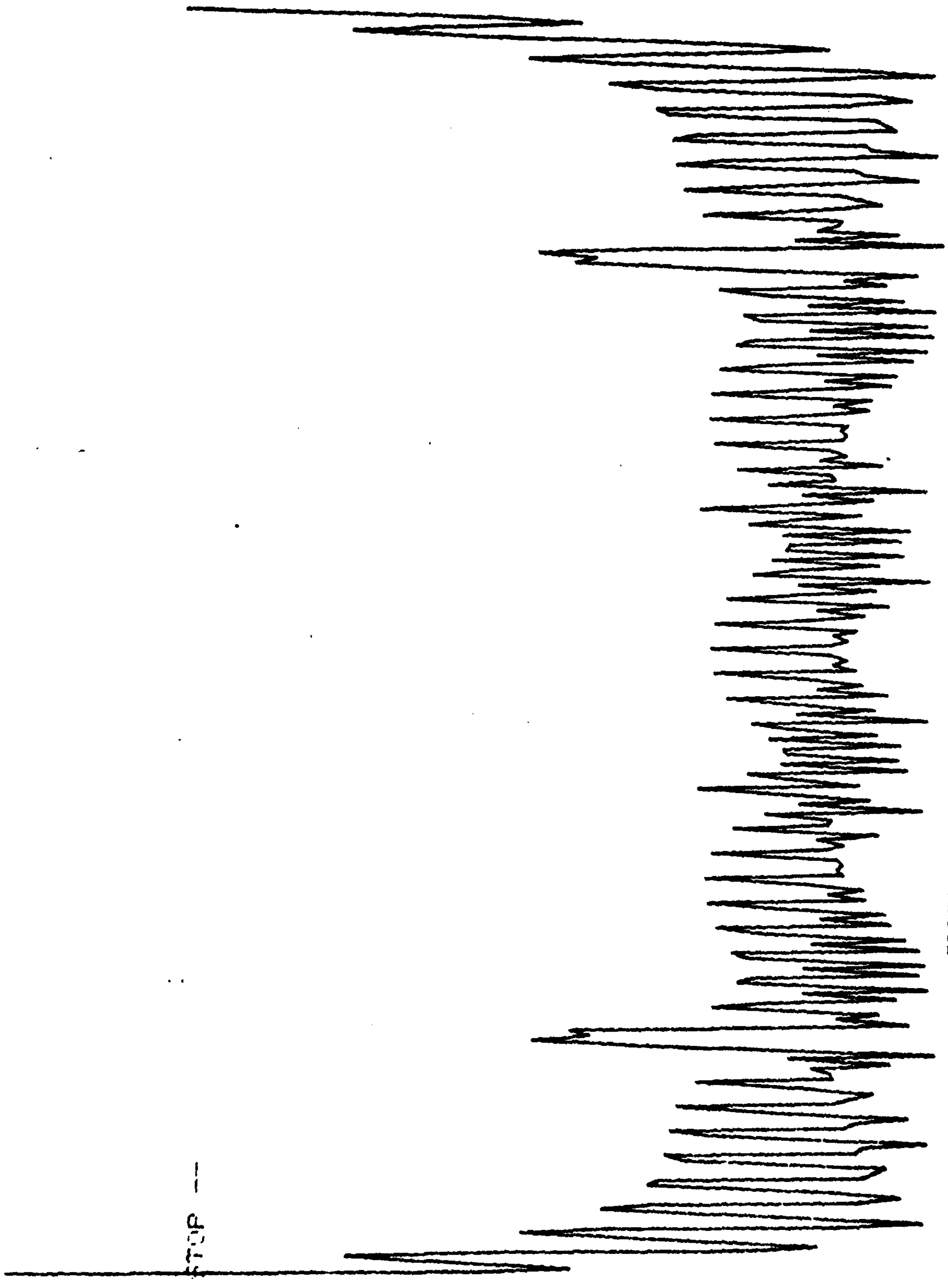


FIGURE 19. CEPSTRUM FOR SIGNAL OF FIGURE 18.

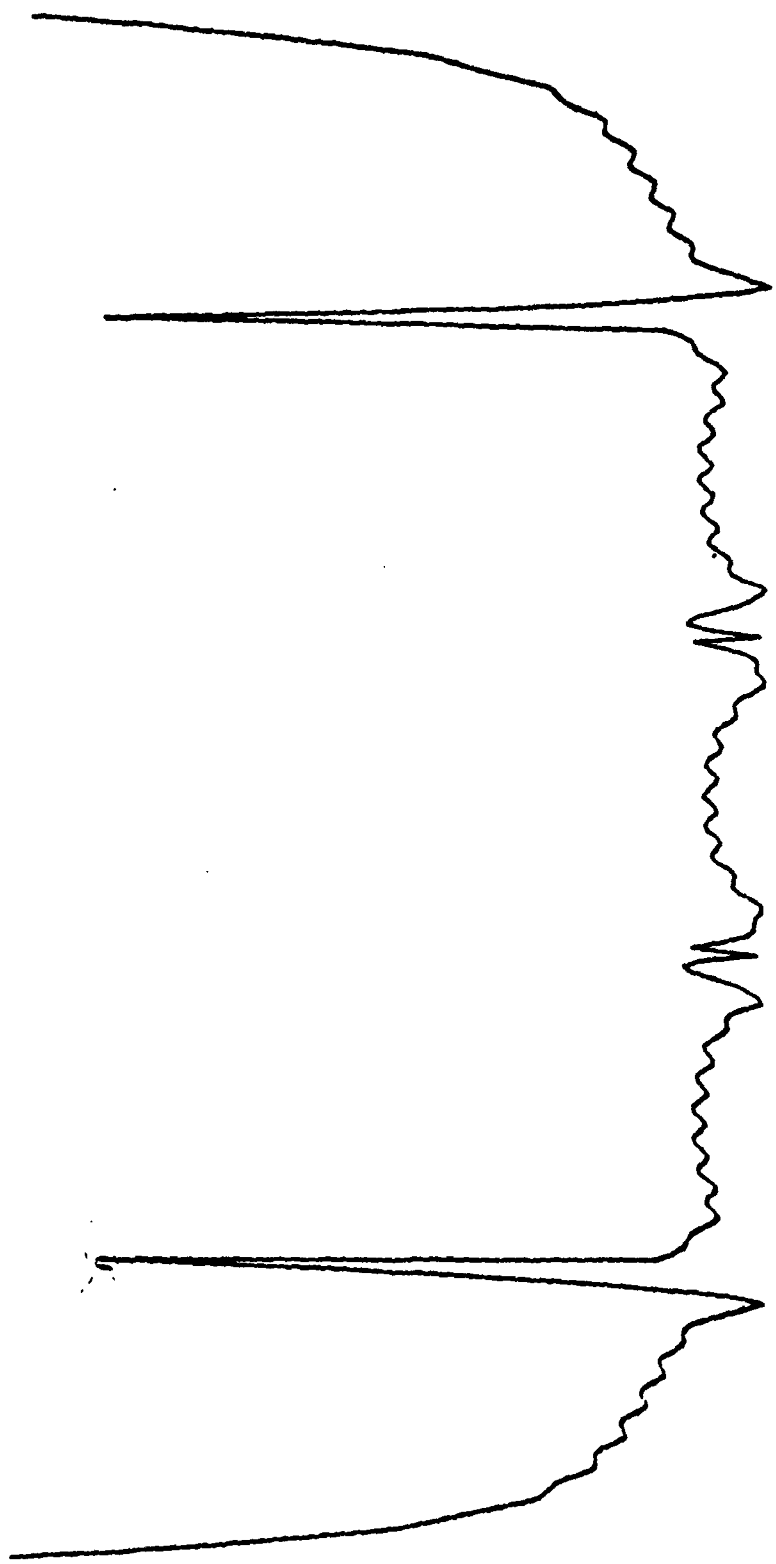


FIGURE 20. ENHANCED CEPSTRUM FOR SIGNAL OF FIGURE 18.

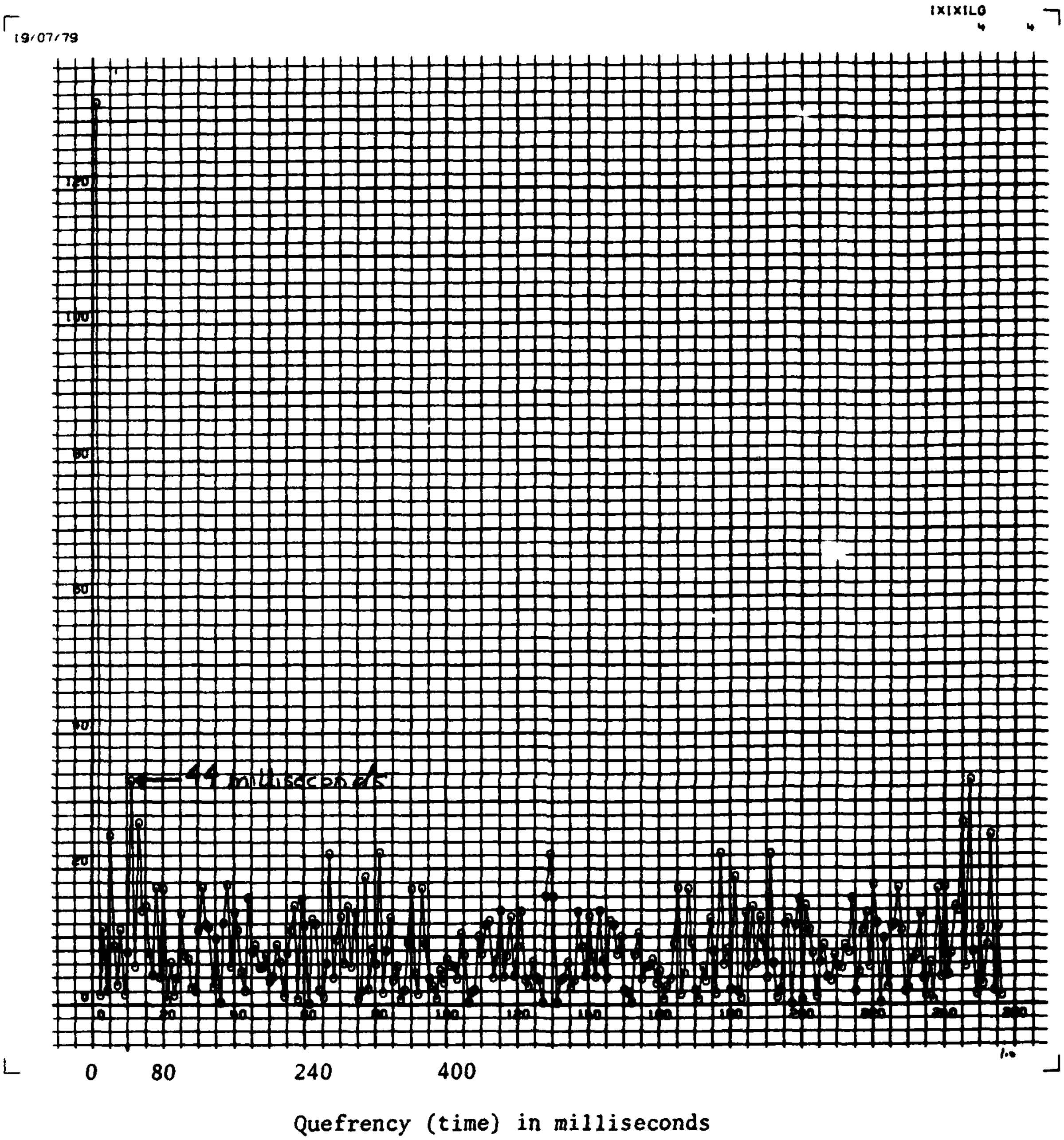


FIGURE 21. CEPSTRUM FOR BROADBAND NOISE ACOUSTIC SIGNALS DETECTED BY MICROPHONES SEPARATED BY 50 FT

Cepstrum analysis does seem to have merit for the signal class of interest. Investigative work to gain a good understanding of cepstrums for this signal class is recommended.

Finally, a series of Figures 22-25, illustrate respectively the time signal, power spectrum, log power spectrum and the power cepstrum for a signal emanated from a speaker. The speaker was pulsed at 40 cycles per second and was located 51 ft from the sensor pick-up which was a microphone and a geophone colocated.

The sum of the two signals has been processed for the Figures 22-25. The cepstral spike at 85 milliseconds yields a range of

$$R = (85 \times 10^{-3}) \left(\frac{1120 \times 375}{1120 - 375}\right) = 48 \text{ ft}$$

Speaker nonlinearities produced energy at 64 hertz and 128 hertz as well as the fundamental driving force of 40 hertz. These nonlinearities produced a cepstral spike at the time of 53.5 milliseconds which corresponds to the time for the acoustic energy to leave the speaker and arrive at the sensor pair. These figures illustrate the potential of cepstral analysis for single sensor ranging. Couple this technique, refined for optimum results, with the tube sensor which is under development at AFATL/DLJF and a potentially excellent fieldable system is conceivable.

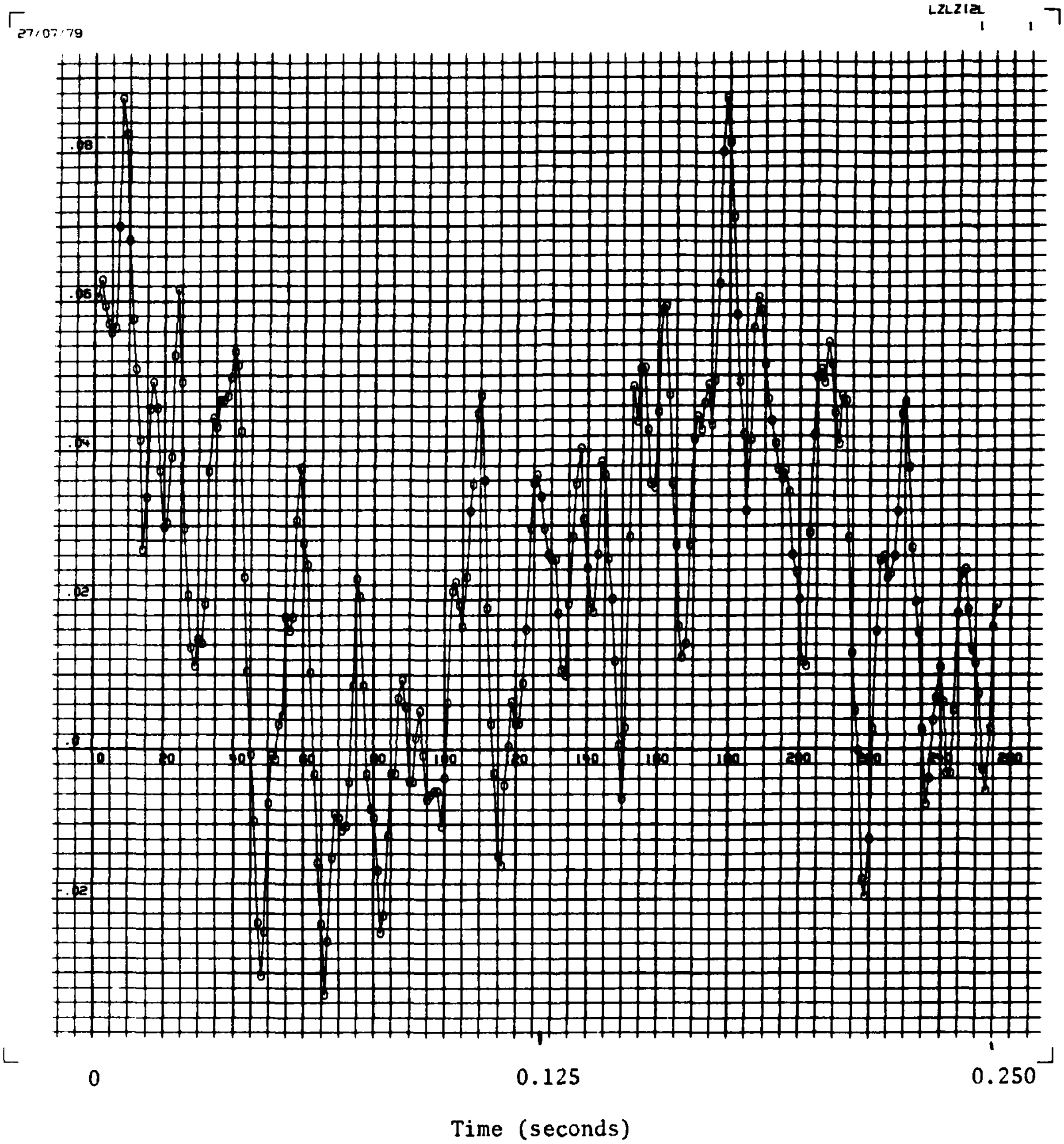


FIGURE 22. TIME SIGNAL EQUAL TO THE SUM OF MICROPHONE & GEOPHONE SIGNALS

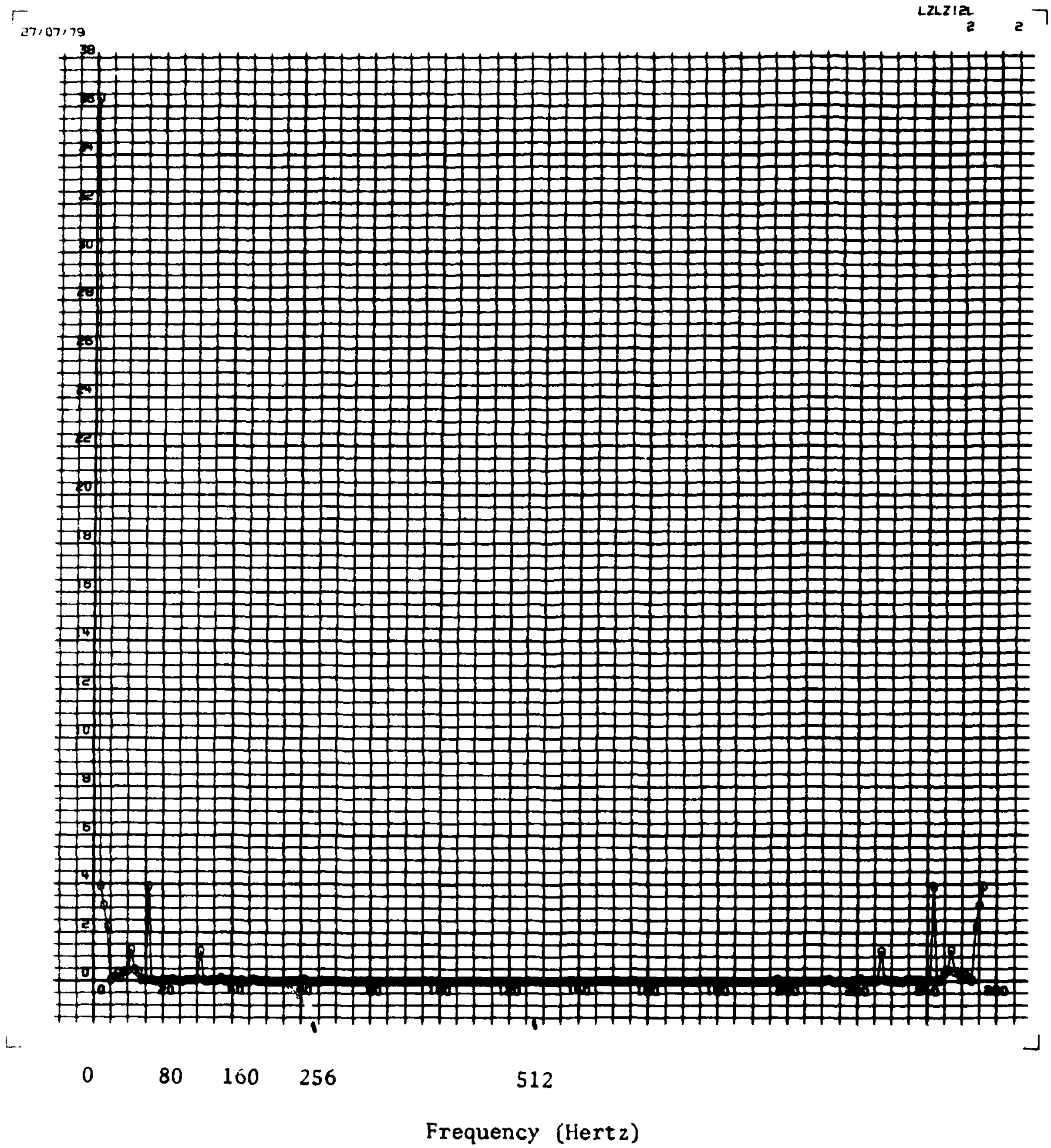


FIGURE 23. POWER SPECTRUM FOR SIGNALS OF FIGURE 22.

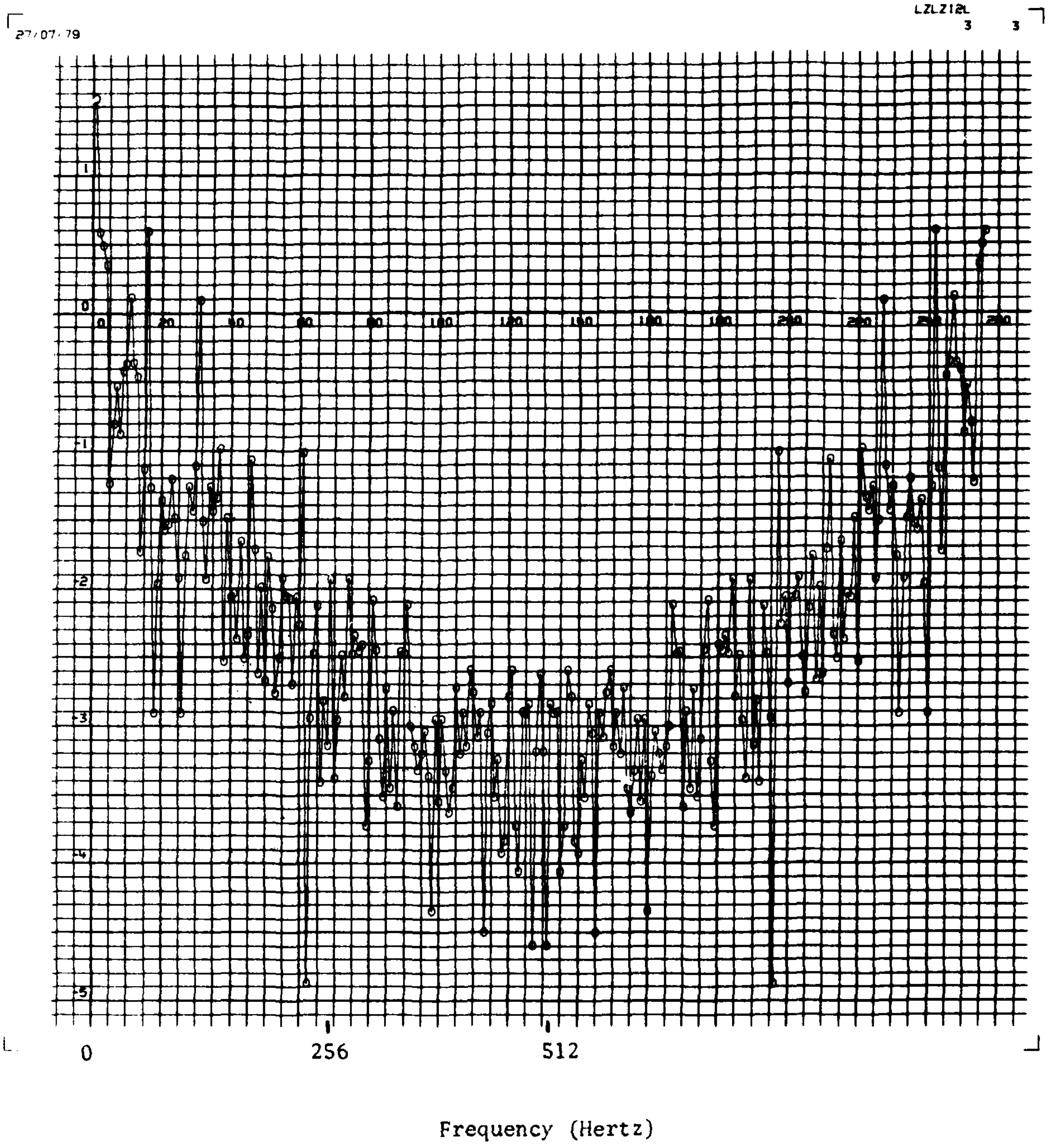


FIGURE 24. LOG POWER SPECTRA FOR SIGNALS OF FIGURE 22.

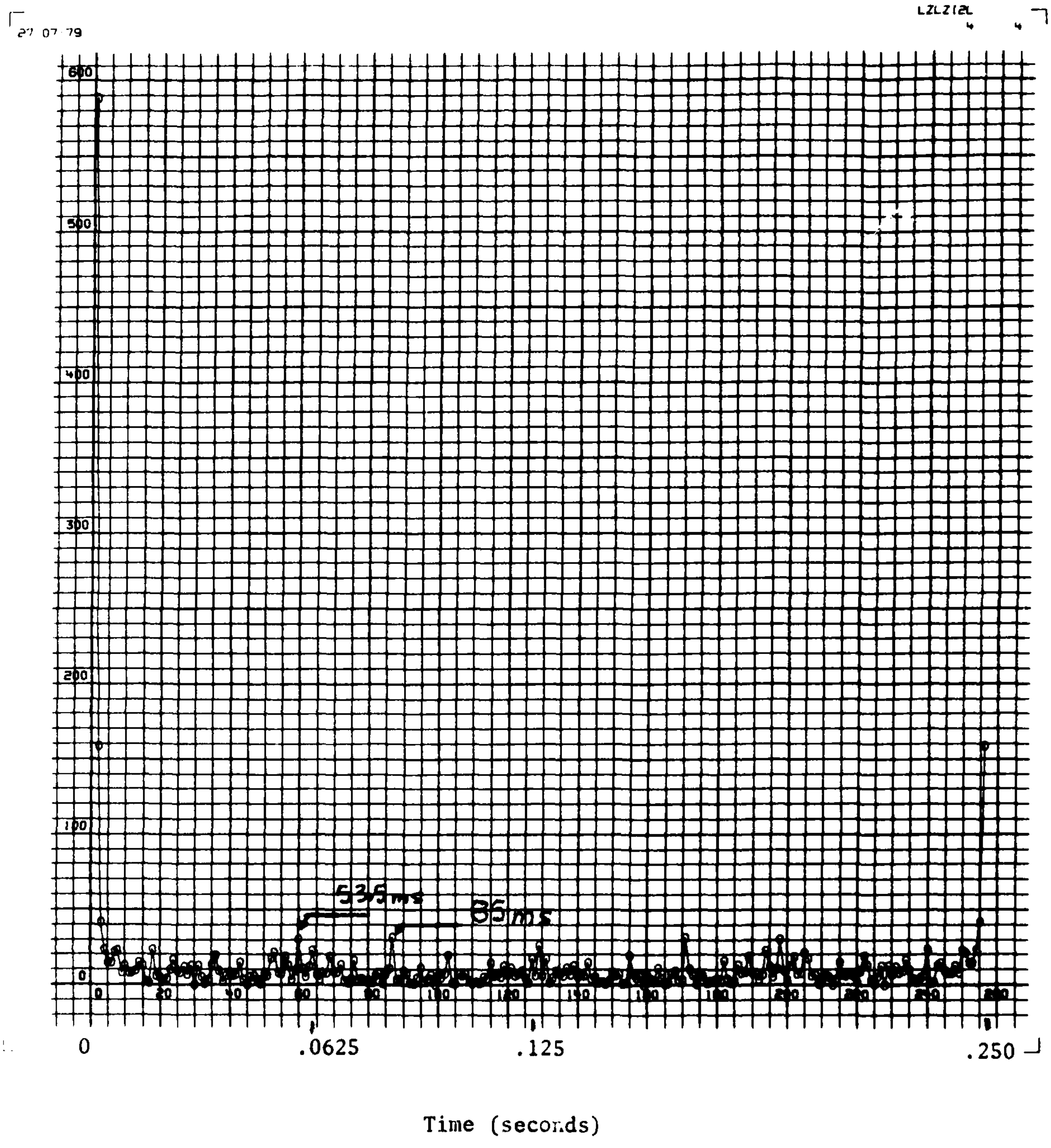


FIGURE 25. CEPSTRAL PLOT FOR SIGNALS OF FIGURE 22.

III. RECOMMENDATIONS FOR FURTHER RESEARCH

Although cepstrum analysis has been reported in depth for pulsive type signals, there has not been any work reported on cepstrum techniques for semi-periodic and semi-coherent sources. It is the purpose of this section to recommend the investigation of the cepstrum approach for analysis of

A. Semi-periodic, semi-coherent sources

B. Mixed signals of similar but different spectral distributions

Table I illustrates the areas of investigation relative to the various classification of sources.

In particular it is recommended to extrapolate the known results for cepstrum analysis for pulsive waveforms by adding signal components that are exponentially damped sinusoidal functions with only one or two complete cycles. As opposed to causal system techniques where no signal input is assumed before t = 0, these signals would be analyzed for segments of data that have the signal present well before and after the analysis period. It is also recommended that the periodic component content which may be acceptable to a cepstrum analysis be determined.

The mathematical analysis for these nonstrictly pulsive signals is not easily accomplished. In fact most analysis approaches assume a time window that selects only one pulse of pulsive data for inspection of the signal. However, the real world data will not be analyzed in this fashion and so this mathematical model does not properly model the situation. For this reason, a computer simulation with artificially synthesized data is recommended for comparison with the mathematical analysis to be developed.

TABLE I

SOURCE CLASSIFICATION	PULSIVE DATA SOURCES	SEMI-COHERENT SEMI-PERIODIC SOURCES	COHERENT PERIODIC SOURCES
Possible techniques for time delay analysis for composite waveforms $s_1(t) + s_2(t)$	1. Cross correlation <u>if</u> waveforms are separable by filtering (well known technique).	1. Cross correlation <u>if</u> waveforms are separable by filtering (well known technique).	1. Cross correlation <u>if</u> waveforms are separable by filtering (well known technique).
	2. Cepstrum for both separable and non-separable waveforms (fairly well known technique).	2. Cepstrum approach not documented (<u>an unknown technique</u>).	2. Cepstrum: very limited application. Not a viable technique.
	$\underbrace{\hspace{6em}}_{\text{Proposed Research Areas}}$		

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FINAL REPORT

A NMR STUDY OF ADSORBED WATER IN THE ANODIZED OXIDE LAYER AND PAPER SPACER OF ELECTROLYTIC CAPACITORS

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ABSTRACT

The nature of adsorbed water in the anodized oxide layer and the paper spacer of electrolytic capacitors has been studied, primarily, through Nuclear Magnetic Resonance (NMR) measurements. Thermogravimetric analysis (TGA) of the anodized aluminum foil has also been carried out with a view to corraborate the NMR data. ^{1}H signal from the paper spacer is much stronger than that from the sealed anodized aluminum sample. The signal from the anodized sample shows a narrow peak and a doublet. The narrow peak is, probably, due to rapidly diffusing water molecules and the doublet due to immobilized water. The signal from the paper sample did not show any splitting and had a line width of 0.07 gauss. The activation energy corresponding to motional diffusion of adsorbed water molecules in the paper sample is 9.2 Kcal./mole. Suggestions for further research in this area with a view to delineate the detailed molecular dynamics of the adsorbed water molecules are given. A brief discussion of the Maxwell-Wagner model of dielectric polarization effect relating to the capacitor is also given.

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I. INTRODUCTION:

The problem addressed in this project is related to the basic understanding of failure mechanisms in aluminum electrolytic capacitors. The motivation for such a study was prompted by the uncertainty about the aluminum electrolytic capacitor's ability to function successfully in Gator Mine application after ten years of storage in a rather uncontrolled environment.

The standard aluminum electrolytic capacitor is rated for approximately 3 years of shelf life. After 3 years storage, the capacitor must be repolarized to reform the capacitor dielectric. The premium grade long life capacitors is rated between 10-20 years shelf life. The oxide film which is the dielectric, is applied to the anode base material of highly purified aluminum through a suitable electrolytic forming process. Under normal operating conditions, the electrolyte (cathode) provides the oxygen required to maintain the oxide film. When the capacitor is charged, leakage paths may exist between the oxide film and the electrolyte due to imperfections in the oxide layer. Under normal conditions, however, the process of charging actually restores and maintains the oxide film, providing a self-healing property which is associated with electrolytic capacitors; but the oxide film produced during the healing process is definitely inferior and more subject to chemical attack. During storage, it is believed that the oxide film deteriorates and deforms due to chemical activity between the oxide film and the electrolyte. It is reasonable to expect that this deterioration is accelerated by high temperature and increases with increased storage time. According to capacitor manufacturers, capacitor aging rate can be estimated using an approximation to Arrhenius equation. In words, the approximation states that the rate of reaction in most chemical reactions doubles for every 8 to 12^{o}C increase in temperature. The deterioration of the anodic oxide layer would be a major factor in failure; however the paper spacer and the cathode foil usually made of not so pure aluminum as the anode might have some role in contributing to the failure mechanism.

The aging of aluminum electrolytic capacitors on shelf is generally believed to be due to the hydration of the aluminum oxide dielectric because of residual water contained in the paper or the impregnated electrolyte and impurities within the aluminum.[1] The process of growing the oxide by the forming electrolyte follows the reaction..[2]

$$2A\ell^{+3} + 3O^{-2} \rightarrow A\ell_2O_3$$

The $A\ell$-$A\ell_2O_3$ interface penetrates into the metal as the anodization process continues with additional reactions possible:

$$2A\ell^{3} + 3H_2O \rightarrow A\ell_2O_3 + 6H^+$$

$$2A\ell^{3} + 3OH^- \rightarrow A\ell_2O_3 + 3H^+$$

According to Alwitt and Hills[3] the dissolution of aluminum oxide probably proceeds via the overall reaction,

$$A\ell_2O_3 + 3H_2O + 2OH^- \rightarrow 2A\ell(OH)_4^-$$

When the oxide has been thinned to its equilibrium thickness, any further dissolution is accompanied by rapid production of new oxide to maintain the equilibrium barrier-layer thickness. This would be an electrochemical process, the anodic reaction being the consumption of metal to form oxide and the cathodic reaction the evolution of hydrogen: i.e.,

$$\text{Anodic:}\quad 2A\ell + 3H_2O - 6e \rightarrow A\ell_2O_3 + 6H^+$$

$$\text{Cathodic:}\quad 2H^+ + 2e \rightarrow H_2$$

$$\text{or } 2H_2O + 2e \rightarrow H_2 + 2OH^-$$

At steady state, the dissolution of oxide would be just balanced by the formation of oxide. The net result would be dissolution of metal and production of hydrogen. It is believed that the application of a hydrated oxide layer after etching is beneficial to protect the anodic foil against corrosion by its natural oxide film.

According to Altenpohl and Post[4], when aluminum foils with hydrated oxide layers are formed, the dielectric grows underneath the hydrate oxide film. In an electrolytic capacitor the hydrated oxide layer is penetrated only partly by the electrolyte, the remainder acting as a dielectric.

For a thorough basic understanding of the failure mechanisms, analysis of the various components of the capacitor by various physical methods would be desirable. Some of these techniques are SEM, TEM, ESCA, TGA, NMR, Auger, IR and so forth. In this project the major experimental effort was through NMR in addition to supportive data through TGA and an attempt at permittivity measurements of a typical electrolyte and the oxide layer. The latter measurements would be useful in delineating the Maxwell-Wagner and Debye polarization effects.

II. OBJECTIVES:

The objectives of this project were:

(1) To survey the relevant literature,

(2) Solid phase Nuclear Mangetic Resonance (NMR) measurements of the oxide layer and the paper spacer impregnated with the electrolyte with a view to characterize the state of water in both,

(3) Thermogravimetric Analysis (TGA) of the anodized aluminum foil with a view to support the findings of NMR measurements, and (4) Permittivity measurements of a representative forming electrolyte and the oxide layer to characterize the interfacial polarization in terms of the Maxwell-Wagner process.

III. SURVEY OF THE RELEVANT LITERATURE:

Some of the significant information derived from the literature relative to the project is already included in the Introduction. In this section additional information which might be useful in assessing the failure mechanisms in aluminum electrolytic capacitors is outlined:

An important aspect in the assessment of electrolytic capacitors is that after a prescribed time at rated temperature both with and without applied voltage, the capacitance, dissipation factor (or ESR) and leakage current shall not have exceeded stipulated limits. A typical requirement is in the military specification MIL-C-62B which states that after 100 hours at 85°C with no applied voltage, the capacitance shall not have changed more than ±10% from its initial value, the ESR shall not be more than 120% of the initial requirement, and the leakage current shall not exceeed 200% of the initial requirement. According to Alwitt and Hills[3], the failures which were due to excessive changes in capacitance, dissipation factor or leakage current on shelf or life test could be ascribed to reactions of the foil-electrolyte system, unaffected by trace contaminants or materials of construction. Analysis of these devices showed that in almost every case at least one of the following phenomena had taken place:

1. Increase in capacitance of the anode foil accompanied by decrease in ability to withstand voltage stress.
2. Increase in cathode foil capacitance.
3. Production of gas.

The mechanical damage which occurs during assembly and winding must be repaired by a burn-in process. It is a known fact that this healing process is much less efficient than the original anodizing process and the type of oxide film produced is definitely inferior and more subject to chemical attack. Corrosion due to $C\ell^-$ is believed to be an important factor in contributing to the failure mechanism of aluminum electrolytic capacitors. $C\ell^-$ is attracted to the anode and there it reacts with the aluminum after penetrating the oxide film. Even 10 ppm in the spacer or electrolyte can lead to high inherent leakage currents which eventually cause a short circuit.[5] According to Altenpohl and Post[4] the presence of a hydrated oxide layer, produced under carefully controlled conditions in double distilled or deionized water, can be extremely beneficial in protecting against corrosion during storage. Its growth critically depends on the water temperature used. Temperatures below about 75^oC result in relatively thin layers consisting of bayerite ($A\ell_2O_3 \cdot 3H_2O$) and other, undefined, aluminum hydroxides. Above 75^oC, X-ray or electron-diffraction photographs reveal the presence of boehmite ($A\ell_2O_3 1H_2O$). The presence of the hydrated oxide layer has another important effect in that it improves the crystallinity, and the purity of the film. The attack by the electrolyte is reduced mainly to the flaws because the polycrystalline film form has grain boundaries which are much less permeable. The crystalline form is believed to be $\gamma - A\ell_2O_3$. Altenpohl and Post[4] report that infrared spectral analysis and differential thermoanalysis (D.T.A.) both reveal the possible presence of trihydrates in films in which x-ray diffraction photos indicated only the presence of boehmite.

According to Burnham et al[6] the charging and discharging mechanisms are complicated, involving both Maxwell-Wagner and Debye polarization as well as true space charge layers involving motions of either electrons and holes or ions and ion vacancies. These come into play at various temperatures. They recommend the use of thermally simulated discharge (TSD) which not only accurately measure the quantity of stored charge, but provides information about the previous charging history. Any variations in the thermal current spectrum can also be used to identify material and process variations which will be of diagnostic value for analysis of failed parts to provide feedback for better manufacturing controls. By this method, the presence of moisture, for example, can be detected.[7]

Fripiat and Touillaux[8] have studied the proton magnetic resonance in boehmite in the temperature reange from $+350^{\circ}C$ to $-145^{\circ}C$. Their study indicates two spin populations, P_n and P_w, to be differentiated. The P_w population belongs to the ordered domain of the oxygen-hydroxyl zig-zag chain while the P_n population represents either extrinsic lattice defects (below $\sim 50^{\circ}C$) or extrinsic and intrinsic defects occuring at a higher temperature. In both these defects the longitudinal relaxation rate is atrributed to fast proton jumps between H_2O^+ units and free orbitals of adjacent oxygen atoms. The transverse relaxation rate is due to the rotation of the H_2O^+ units. At room temperature, the P_n population is represented in the n.m.r. absorption spectrum by a narrow band (second moment < 0.2 gauss^2) while the wide band (second moment $\simeq 16.5$ gauss^2) is due to the P_w spin collection. Each population is characterized by a different magnetic environment and exchange between these two populations occurs readily. Mata and Fripiat[9] have carried out dielectric measurements on compressed boehmite pellets in the frequency range 800 to 16,000 Hz at various temperatures. Their results reveal a well marked absorption process by ion-pair defects. The activation energy of these defects is almost the same as that obtained for the deuteron diffusion in the lattice. This suggests ion pair defects being responsible for the diffusion process. Literature search has revealed neither N.M.R. nor dielectric studies on bayerite.

IVA. N.M.R. STUDY OF THE ANODIZED ALUMINUM FOIL:

Pulsed NMR studies in the solid phase is a useful technique for the study of the surfaces of solids. Such studies are also useful to measure activation energies and correlation times for dynamic processes in small molecules. In particular with reference to the present project the state of water adsorbed in the oxide layer and also the study of protons belonging to the structure of the solid can be obtained by measuring the spin-lattice (T_1) and transverse (T_2) relaxation times. T_1,T_2 relaxation times can be quantitatively related to dipole-dipole, spin-coupling and other interactions. Information about molecular diffusion can be conveniently obtained by measurement of T_1, the Hahn spin echo, the modified Carr-Purcell technique and the pulsed field gradient technique which has several advantages over the other methods.[10] Second Moment studies (Wide Line NMR) have the capabilities of revealing quite considerable details of the distribution of nuclei on surfaces and this type of study should compliment direct measurements of T_1 and T_2.[11]

The NMR system available for the study was the Varian XL-100. The frequency sweep on this instrument is 5 KHz which corresponds to a field sweep of 1.25 gauss. With this limitation, broad NMR lines could not be observed. The most versatile method for measuring T_1's over a wide range of values is the pulse Fourier transform (FT) method using the commonly employed 180°, τ, 90° sequence. Unfortunately this option on the XL-100 was not operational. The progressive saturation method in the C.W. mode with its inherent limitations could be used to measure T_1.

Sealed and unsealed samples of anodized aluminum were prepared. The method used was the sulfuric acid anodization described in the literature.[12] The procedure consisted in anodizing 7" x 15" rectangular foil in a 15% by weight of sulfuric acid in double distilled water. The cathode was a piece of lead foil of the same area as the aluminum foil. The current density was 12 amperes/sq. ft. The voltages applied ranged from 11 to 14V. Both the electrodes were cleaned with alcohol and dried before inserting them into the electrolytic bath. The time of anodization was 30 minutes and then the samples were rinsed thoroughly in distilled water. The unsealed samples were dried right away. The sealing procedure consisted in baking the sample in boiling distilled water for 20 minutes. It was noticed that the samples prepared by the above procedure came out pretty brittle. Earlier attempts at anodizing were done in a beaker lined with lead. The aluminum foil a 4" x 4" square piece was inserted in the center of the beaker. The working voltage ranged from 6 to 8 volts. The other parameters were the same as above. The samples prepared this way were not brittle. The unsealed and sealed samples were examined under the Zeiss-optophot optical microscope under a magnification of (x400). There was no noticeable difference in the patterns. A SEM photograph at (500x) of the unsealed sample is shown in Fig. 1.

N.M.R. Results and Interpretation:

Proton resonance (^1H) signal of a sealed anodized aluminum sample grown in the laboratory as described above as well as that of the anode foil from a capacitor are shown in Figs. 2 and 3 respectively. These signals were obtained at room temperature in the c.w. mode after signal averaging over a large number of scans. The sample obtained from the capacitor was from a MEPCO 22 mfd. 52 W. volts electrolytic capacitor. This sample was vacuum dried for a week in a dessicator over a bed of calcium carbonate before being introduced into a 12 mm O.D. N.M.R. sample tube. The signal shown in Fig. 2 is that of the anodized sample grown in the beaker as described above and air-dried. The singal from the laboratory sample shown in Fig. 2 after 535 scans extending over a period of approximately 15 hours is much stronger than the signal obtained

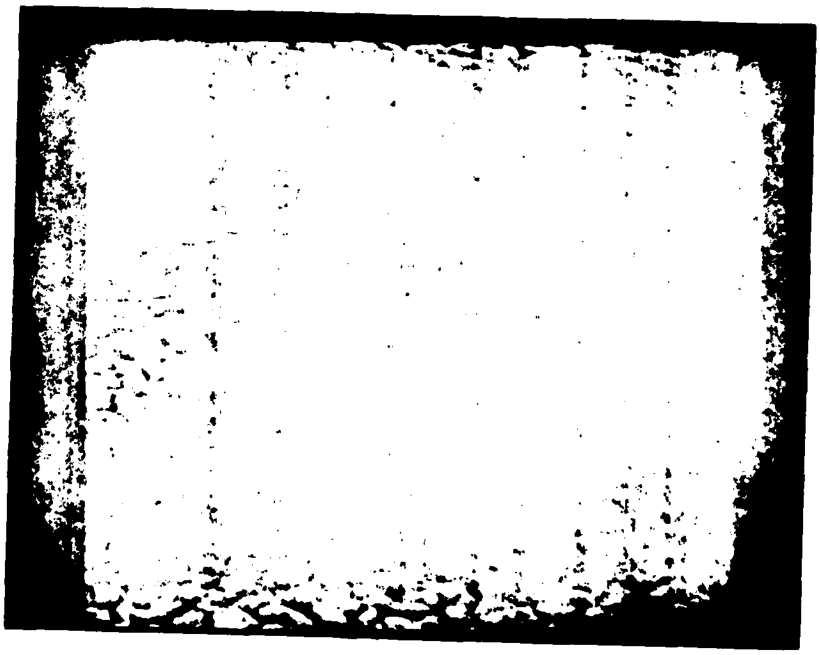

Fig. 1: SEM photograph at (500x) of unsealed laboratory sample of anodized aluminum.

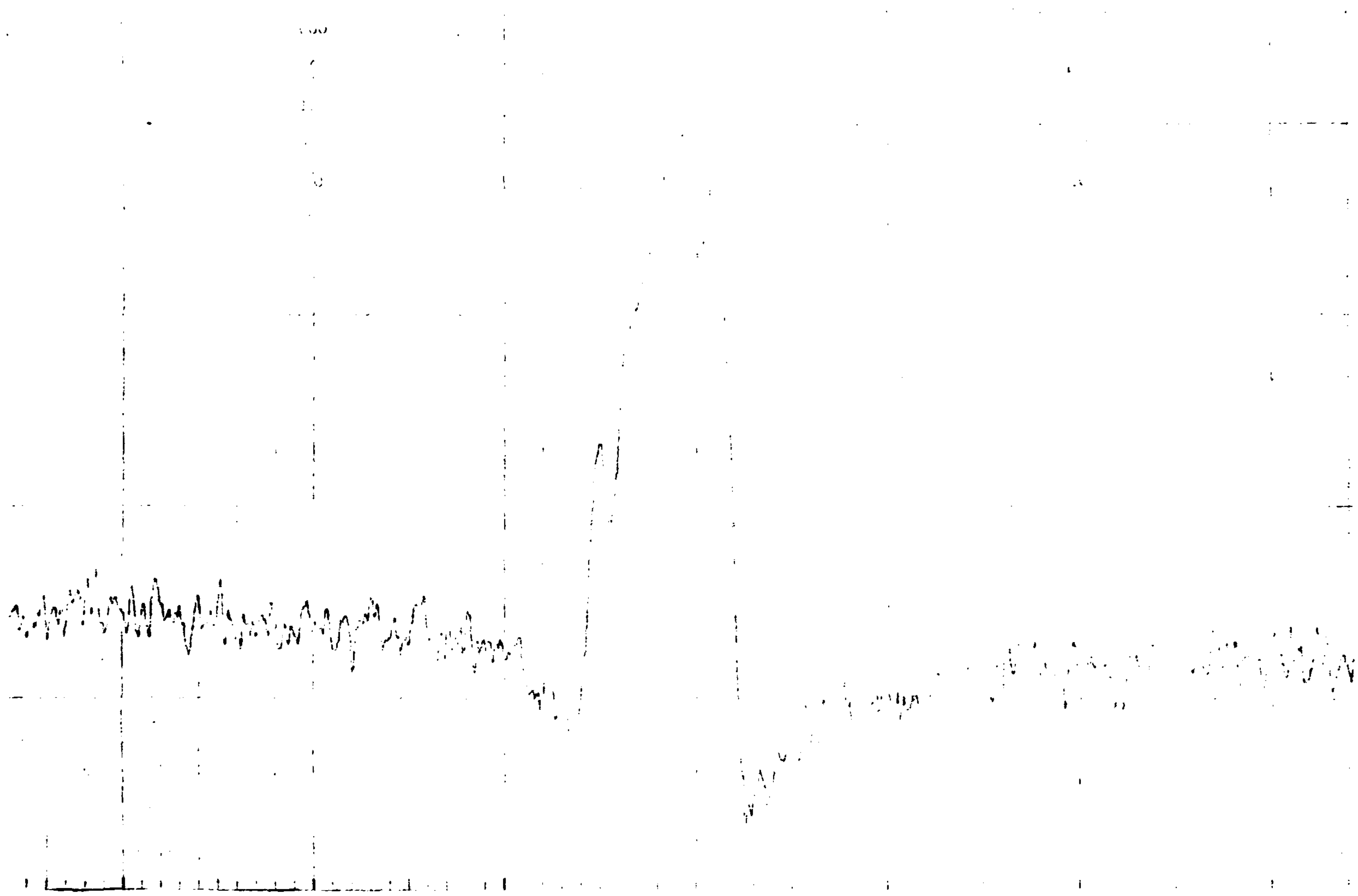

Fig. 2: **Proton resonance** (^1H) of **sealed** anodized aluminum in the C.W. mode after 555 scans; sweep **width: 1 cm = 100 Hz.**

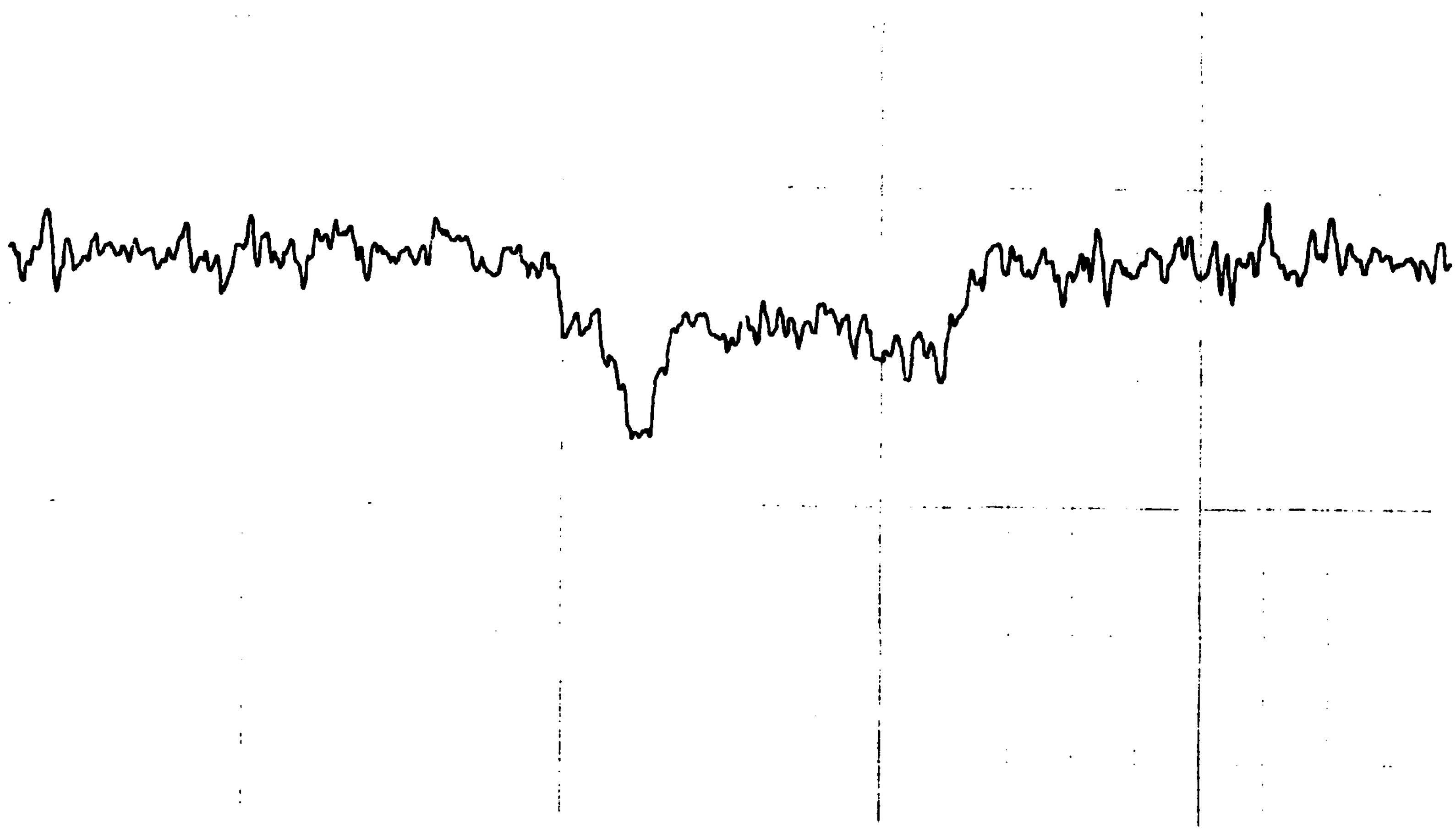

Fig. 3: Proton resonance (^1H) of the anode foil of a MEPCO 22 m.f.d. 52 W. volts electrolytic capacitor in the c.w. mode after 748 scans; sweep width: 1 cm = 100 Hz.

from the MEPCO sample after 748 scans. This finding corraborates, somewhat, with the results of TGA analysis described below in Section V. The proton signal of the laboratory sample shown in Fig. 2 shows a sharp peak and a doublet to the right of it where as no such sharp peak is indicative in the MEPCO sample. As the signal shown in Fig. 3 of the MEPCO sample is very weak the measurements need to be carried to a great many number of scans before any definite conclusions can be drawn as to the absence of the narrow peak.

In the laboratory sample the spectrum of which is shown in Fig. 2 the narrow peak could be due to rapidly diffusing water molecules and the doublet to the right due to immobilized water. Thus there could be two kinds of water. In order to confirm this one needs to carry out the measurements to low temperature and also study the sample after it is deuterated. Freezing should reduce the intensity of the narrow line and it might finally disappear. In the deuterated study it would be easy to substitute the protons responsible for the sharp line but practically impossible to substitute the protons responsible for the doublet (immobilized water). The sharp line then should disappear. Thus measurements at low temperatures and that on deuterated sample would be added proof of different kinds of water. Because of the paucity of results no further interpreation is attempted.

At the outset we had planned on making T_1 vs temperature measurements of these samples with a view to calculate the activation energy involved in the process; but this plan could not be carried through as the availability of the XL-100 was very limited. The XL-100 is heavily scheduled for C-13 work on liquid samples. The possibility of observing the proton resonance of boehmite ($A\ell_2O_3 \cdot 1H_2O$) is ruled out as the proton line width corresponding to boehmite is rather broad[9] and outside the range of the instrument. In conclusion further study is needed to establish how water is bound in the oxide layer. The few measurements that we were able to make does, however, indicate the presence of different kinds of water adsorbed in the anodized oxide layer.

IVB. N.M.R. STUDY OF THE PAPER SPACER IMPREGNATED WITH THE ELECTROLYTE:

A section of the paper spacer from the same MEPCO capacitor was rolled into a cylinder and introduced into a 12 m.m. O.D. NMR sample tube. As the external fluorine lock of the spectrometer was not functioning when this sample was studied, the paper was rolled over a 5 m.m. deuteron lock tube and introduced into the 12 m.m. tube. The sample was vacuum dried for a week to eliminate the possibility of the sample absorbing moisture from the air. The NMR spectrum of the dried sample is shown in Fig. 4. The sweep width used was 5 KHz and the sweep time was 250 seconds. Proton signal was easily recorded for this sample without the need for signal averaging unlike in the case of the anodized aluminum sample. The narrow spike in the spectrum to the left of the broad line is due to the residual water in the deuteron lock tube. The line width of the proton resonance is about 0.07 gauss and corresponds to a transverse relaxation time T_2 of 1.12 ms. No splitting was observed unlike in the case of the anodized sample. This indicates that only one type of adsorbed water molecules is present in the paper sample. T_1 measurements on this sample was made using the progressive saturation method.[13] This method involves the measurement of peak height as a function of the RF voltage applied to the sample coil. To find the value of J_1H_1 from the RF voltages, a standard of known relaxation time is needed. For this, a 16 mM solution of copper sulfate in water was used as suggested in the reference. There is an inherent error in this approach for the sample on hand, as the paper sample had to be wrapped around a 5 m.m. deuteron internal lock tube and could not be packed tightly in the sample tube. The method suggested in reference 13 is essentially good for liquids or a solid introduced into the sample tube in compressed powder form occupying the same volume as the calibra-

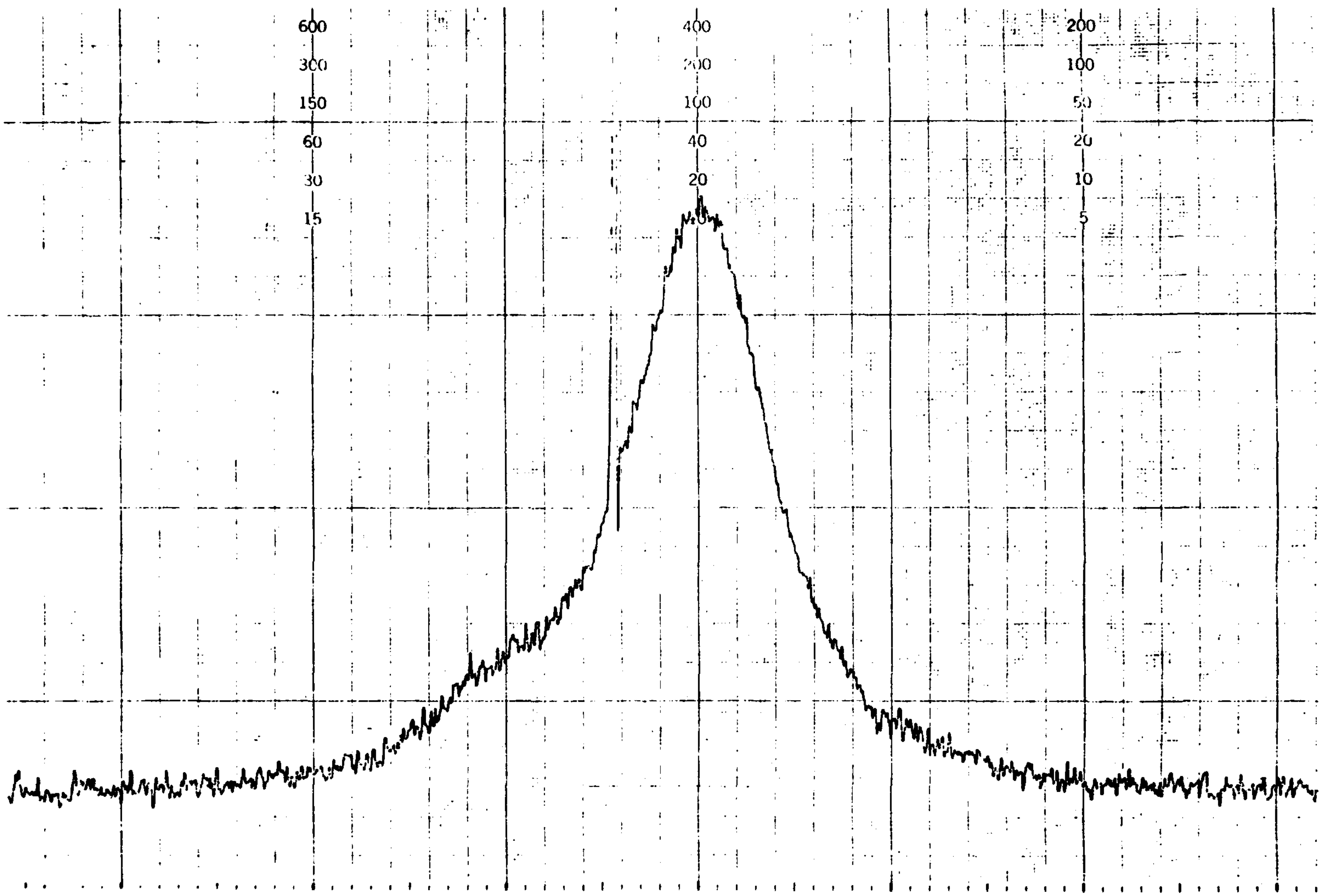

Fig. 4: Proton resonance (^{1}H) of vacuum dried paper spacer of a MEPCO 22 m.f.d. 52 W volts electrolytic capacitor in the c.w. mode after a single scan; line width: 0.07 gauss.

tion liquid sample. So the T_1 measurements would not be accurate as in the case of the 180^o, τ, 90^o pulse method. From the measured values of T_1 and T_2, the activation energy corresponding to motional diffusion of adsorbed water molecules in the paper sample was calculated using the method outlined by O'Reilly and Poole.[14] The spin-lattice relaxation time, T_1, by the progressive saturation method is $T_1 = 8.4$ seconds and the activation energy corresponding to motional diffusion of adsorbed water molecules is 9.2 kcal./mole.

V. TGA OF THE ANODIZED SAMPLES:

With a view to support the findings of N.M.R. measurements relative to the presence of water in the various anodized samples, the same samples were analysed by the method of thermogravimetric analysis (TGA). Both the commercial MEPCO sample and the laboratory sealed sample anodized in the beaker at a voltage of 6-8 volts and a current density of 12 A/sq.ft. were heated in helium atmosphere from room temperature ambient to 600°C at the rate of 20°C per minute. The unsealed anodized sample prepared at 12 volts at the same current density was heated in an air atmosphere to 400°C at the rate of 10°C per minute. The sealed laboratory sample showed a steady loss of weight from 30°C to 220°C amounting to 4.5% of total sample weight; from 220°C to 600°C the weight loss is much more gradual amounting to 2.8% additional weight loss. Therefore from ambient to 600°C for this sample the total weight loss amounts to 7.3%. For the commercial MEPCO sample the weight loss was very slow and steady from ambient to 600°C amounting to 0.2% of total weight. The weight loss in both these samples corresponds closely with the NMR data in the sense that the proton resonance signal of the sealed laboratory sample was much more intense than proton signal of the MEPCO sample which was very weak. As noted above in both the samples the drop in the weight loss curve was gradual and there was no sudden drops near 350°C and 550°C as reported by Altenpohl and Post[4] in their study of hydrated aluminum oxide films. The peaks at 350°C and 550°C in their study are characteristic of the mineral bayerite ($A\ell_2O_3 \cdot 3H_2O$) and the mineral boehmite ($A\ell_2O_3 \cdot 1H_2O$) respectively. The unsealed anodized sample showed a gradual weight loss of 3 to 4% which is less than that of the sealed sample. This is reasonable to expect as one might expect more loss of water from the sealed sample which was baked in boiling water for 20 minutes after anodizing. The TGA curves did not show any sudden changes indicative of a phase transition. N.M.R. relaxation time measurements as a function of temperature would be a good tool for the study of phase transitions in solids.

VI. PERMITTIVITY AND LOSS MEASUREMENTS AND THEIR CORRELATION WITH MAXWELL-WAGNER POLARIZATION:

As mentioned briefly in Section III the charging and discharging mechanisms in the capacitor are complicated, involving various effects such as Maxwell-Wagner, Debye polarization and etc. In particular it was felt worthwhile to explore the consequences of Maxwell-Wagner interfacial polarization since from a dielectric point of views, the problem is essentially one of a heterogeneous dielectric. For an analysis of this effect one needs to know the permittivity and the dissipation factor of both the oxide layer and the electrolyte. An attempt was made to measure these parameters using the HP4282A Digital High Capacitance Meter. A representative electrolyte was prepared for this purpose as suggested in reference 3. It consisted of 17% ammonium pentaborate in ethylene glycol. It was noticed that the solute was not very soluble and it was necessary to heat the sample to an elevated temperature for the solute to dissolve. On cooling down to room temperature the ammonium pentaborate did not precipitate out. The measured dielectric constant was extremely high about 600,000! This high value obtains both at a low frequency of 120 Hz and also at 1 MHz. According to the literature,[15] ammonium pentaborate is piezoelectric and pyroelectric but there is no mention of it being ferroelectric.

In view of this, the high value of the dielectric constant that was measured in indeed intriguing. The dielectric constant of ammonium pentaborate single crystal is about 6.5 and that of ethylene glycol 37. It was felt that heating the sample might have affected the measurement. Therefore another solution was prepared with 1.7% ammonium pentaborate in ethylene glycol. Although there was no difficulty in solubility at this low concentration, the capacitance of the electrolyte sample showed a time dependent effect. It measured 15μf at the start and gradually increasing to 21.5μf after a day in a liquid cell whose air capacitance was 35 p.f. The measured dielectric constant is still high - 614,000 about the same as the precious measurement. The dissipation factor measured was 1.62. An attempt to measure the dielectric constant of the oxide layer using a General Radio dielectric sample holder was not successful in view of the very thin oxide layer. Because of the difficulty in getting the dielectric data, what follows is a brief academic discussion of the Maxwell-Wagner model of interfacial polarization: In a heterogeneous material, interfacial polarization often called the Maxwell-Wagner effect[16,17] arises from the accumulation of charge at the interfaces between phases which differ from one another in dielectric constant and conductivity. For a two layer dielectric in particular, this effect occurs when the product of the dielectric constant ε_1 of one phase and the conductivity σ_2 of the second phase is unequal to the product of the dielectric constant ε_2 of the second phase and the conductivity σ_1 of the first phase, that is, $\varepsilon_1\sigma_2 \neq \varepsilon_2\sigma_1$. This accumulation of charge requires flow of current through the dielectric phases, a process which may require seconds or minutes so that it is usually observed only at very low frequencies. The presence in a capacitor of two phases may give rise to an apparent dielectric constant e' and loss factor e''. e' and e'' for the material as a whole are:[18]

$$e' = e_\infty \left(1 + \frac{K}{1+\omega^2\tau^2}\right) \text{ and } e'' = \frac{e_\infty K\omega\tau}{(1+\omega^2\tau^2)}$$

where

$$e_\infty = \varepsilon_1\left[1 + \frac{3q(\varepsilon_2-\varepsilon_1)}{(2\varepsilon_1+\varepsilon_2)}\right]$$

$$K = \frac{9q\varepsilon_1}{(2\varepsilon_1+\varepsilon_2)}$$

$$T = \frac{(2\varepsilon_1+\varepsilon_2)}{1.13\text{x}10^{13}\sigma_2}$$

where σ_2 is expressed in ohm^{-1} $cm.^{-1}$, and q is the volume fraction of phase 2, and $\omega = 2\pi f$ where f is the source frequency. The above equations are identical in form to that given by Debye equations[19] for dipolar polarization. The particular form of the above equations derived by Wagner[16] are for spherical particles having real dielectric constant ε_2 and conductivity σ_2 and negligible σ_1. According to Sillars[18] the presence of a minute amount of conducting impurity in the form of fine needles could produce a serious loss at low frequencies, although the effect of the same quantity of impurity in spherical form would be negligible. In any event small quantities of impurities may seriously affect the dielectric properties of the composite system. If the phases are present as parallel slabs filling a parallel-plate capacitor, the effects may easily be analyzed in terms of an equivalent electrical circuit.[20] Mata and Fripiat[9] in their dielectric study of boehmite ($A\ell_2O_3 \cdot 1H_2O$) have measured the loss tangent as a function of temperature in the frequency region 0.8 to 16 KHz. The loss tangent peak ascribable to Debye dipolar absorption moves towards lower temperature at lower frequencies. For example in their measurements, the loss tangent peak is around 100°C for a measuring frequency of 800 Hz. From the trend it is quite likely that the loss tangent peak would move near room temperature at lower measuring frequencies such as the power frequency. It is also interesting to note that in their study, the amplitude of the Debye dipolar absorption is almost constant whatever the frequency and this they ascribe to ion pair defects. Proton diffusion process is also ascribed to these defects. The possibility of similar mechanisms in the anodized oxide layer should be looked into.

VII. RECOMMENDATIONS:

In this project, an attempt has been made to understand the nature of the adsorbed water in the anodized oxide layer and the paper spacer through Nuclear Magnetic Resonance studies. Polarization effects have been addressed to through Dielectric studies. This initial study needs to be continued by making more elaborate NMR measurements. The specific NMR measurements are i) Proton T_1 vs temperature measurements of the sealed and unsealed anodized samples using the more accurate 180°, τ, 90° pulse method, ii) T_2 and second moment studies as a function of temperature, iii) T_1, T_2 measurements of deuterated oxide samples, iv) T_1, T_2 measurements of the Aℓ nucleus of the oxide layer, and v) T_1 vs temperature measurements of the paper spacer by the pulse method. The above measurements need to be done on commercial samples of different manufactures. The direct measurement of diffusion coefficient of the adsorbed water molecules would also be helpful. By such exhaustive studies, the detailed molecular dynamics of the adsorbed water molecules can be delineated and the related activation energies and correlation times estimated.

On the dielectric problem, the unusually high dielectric constant of the electrolyte (ammonium pentaborate in ethylene glycol) needs looking into. Before any conclusions can be drawn, one needs to measure the electrolyte in a GR 1620A high accuracy capacitance bridge. The problem of measuring the permittivity of the oxide layer may, perhaps, be solved by isolating the oxide film from the aluminum in an iodine-methanol solution[21] which is believed not to attack the oxide layer. Then the electrode contacts can be made directly on both sides of the oxide layer and the capacitance measured in a GR 1620A capacitance bridge.

Further studies that could be useful are: i) add a halogen such as chlorine to observe any corrosion effects and ii) study of chlorine contamination by NMR and also by Nuclear Double resonance techniques.

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FINAL REPORT

ON REMOTE SENSING OF THE ATMOSPHERIC TEMPERATURE: AN ANALYSIS OF THE DISCREPANCY BETWEEN THE MEASURED AND CALCULATED VALUES OF THE RADIANCE

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ON REMOTE SENSING OF THE ATMOSPHERIC TEMPERATURE: AN ANALYSIS OF THE DISCREPANCY BETWEEN THE MEASURED AND CALCULATED VALUES OF THE RADIANCE

by

Madhoo Kanal

ABSTRACT

An attempt is made to analyze the discrepancy between the measured values and calculated values of the radiance. In the ground truth analysis of the satellite temperature sounding of the atmosphere by the Defense Meteorological Satellite, McClatchey of AFGL has shown that the discrepancy is of systematic nature. A possible explanation has been suggested by Dr. J. King of AFGL that in the calculated values of the radiance a black body type of a radiator may not represent the appropriate source function for the equation of transfer. Following that suggestion, we have derived the appropriate equation relating the discrepancy of the radiance to the deviation of the source function from the black body function. Some specific examples of possible techniques for the source function are suggested based on expansions about the e-folding pressure level. The e-folding pressure is defined as the quantity $P^* = K_\nu^{-1}$, where K_ν is the averaged absorption coefficient. In particular, the direct approximation is obtained by replacing the transmittance function by a delta function. In that case, we show that the deviation of the radiance is exactly equal to the deviation of the source function from the black body function.

ACKNOWLEDGMENTS

The author would like to thank the Air Force Geophysics Laboratory, Air Force Office of Scientific Research, and USAF Southern Center for Electrical Engineering Education for providing him valuable summer support, which has resulted in considerable achievement in advancing the transfer theory and its ramifications in the areas of interest, inter alia to Air Force systems, Electrical Engineers, neutron transport theorists and plasma physicists. He also would like to thank Drs. Robert McClatchey and Jean King of AFGL, Hanscom AFB for providing every possible convenience and a working atmosphere which enabled the author to put a concentrated effort in his research. In particular, he would like to thank Dr. Jean King for many useful discussions.

I. Introduction

It is said that if the theory and the experiment agree perfectly with each other, then there is something wrong either with the theory or the experiment. In general, therefore, one would expect the theory to be in approximate agreement with the experiment and hopefully the discrepancies between the two would be randomly distributed so that on the statistical scale a representation of the reality is achieved. However, if the discrepancies between the two is of consistent nature, then it behooves one to look for the cause in terms of either erroneous values of the input parameters used or perhaps neglect of accounting for all possible important physical processes. It appears that in the ground truth analysis of the satellite temperature of the atmosphere[1] there is a consistent discrepancy between the measured values of the radiance and the calculated ones. The consistency of the discrepancy is clearly exhibited by the fact that majority of the calculated values are higher by as much as 15% than the measured values (see Table 1). Further confirmation of the consistency is provided by another fact that the measurements involved various locations, such as, Barking Sands, Pt. Mugu and Kwajalein on different dates and times. Furthermore, the molecular absorption centered at frequency (cm^{-1}) windows 668, 676, 695, 707, 727 and 746 is such that the numerical differences exhibit the trend as shown in Fig. 1. Among all the channels reasonable agreement occurs only for the channel at 676 cm^{-1}. Now, the two important terms involved in the radiative transfer calculations of the radiance are the transmittance of the atmosphere and the law that governs the emission properties of the medium which relates the temperature to the frequency. If the medium is presumed to be a black body type, then the Planck's law should be the appropriate one to be used as the source function. On the other hand if the absorption cross sections are in error then that error will be propagated in the calculations of the transmittance. Overall, if we consider a unit volume in space, then the portion of the radiation not absorbed must be accountable for the purpose of satisfying the law of conservation of energy. Now the equation of radiative transfer[2] is just another representation of the law of conservation of energy in which the left hand side accounts for the loss of radiation by free flow and the loss due to absorption, while, the right hand side represents the radiation gained from flow into the volume. This continuity must always be maintained in the steady state, so that if we fix the transmittence of the atmosphere then any changes in the source function will result into the corresponding changes in the radiance. Thus, the source function plays a crucial role in the transfer theory. It has been suggested by Dr.J.King of AFGL that the discrepancy in the calculated and observed values of radiance, as exhibited in Fig. 1, may be accountable by a suitable emission law which is different from the black body type of a radiator. We shall follow that suggestion and attempt to arrive at some conclusions and make recommendations as to the possible nature of that law. Let us first point out that the source function would be a black body if the optical density of the matter interacting with the radiation field is so high that the assumption of a Local Thermodynamic Equilibrium (L.T.E.) is valid. In that case, we can associate a local temperature to each point and relate the source function $S_\nu(x)$ and the absorption coefficient as, $\sigma_\nu(x)$: of thermodynamic equilibrium:

$$S_\nu(x) = \sigma_\nu(x)\, J_\nu(T(x)),$$

Table 1. COMPARISON OF MEASURED WITH COMPUTED RADIANCES FOR CASES STUDIED *

	Location	Date	θ°	668	676	695	707	727	746
calc.	Barking sands	2/25/75	4.5	55.1	41.9	45.1	65.0	94.9	100.3
meas.	22.0N 159.8.W	9531		54.1	42.5	41.5	57.4	79.9	95.0
calc.	Pt. Mugu	2/18/75	9.4	57.8	45.0	44.9	58.3	76.6	98.6
meas.	34.1N 119.1W	8531		57.6	46.1	43.1	52.4	71.3	86.0
calc.	Kwajalein	2/28/75	0.5	57.0	42.6	46.5	68.0	97.5	101.8
meas	8.7N 167.7E	8531		55.1	42.2	41.7	59.5	83.0	98.4
calc.	Kwajalein	2/27/75	37.1	58.7	43.7	44.6	64.3	83.9	98.1
meas	8.7N 167.7 E	9532		56.0	43.7	39.9	56.6	77.0	95.0
calc.	Barking Sands	2/24/75	37.0	54.7	42.3	43.1	60.6	80.2	95.8
meas.	22.0N 159.8.W	9532		53.1	42.6	39.0	53.6	71.8	88.6
calc.	Barking Sands	2/18/75	37.0	58.6	44.5	45.1	61.4	79.6	94.5
meas		9532		54.8	43.6	40.3	53.3	71.0	86.2
calc.	Barking Sands	2/26/75	46.4	57.3	43.4	43.3	59.5	79.4	95.1
meas.		8531		54.9	44.2	40.0	52.7	73.8	89.7
calc.	Kwajalein	2/20/75	27.5	59.5	44.5	46.6	66.9	85.9	101.1
meas.		9532		54.4	42.4	40.8	60.9	80.7	97.5
calc.	Kwajalein	4/1/75	22.6	57.7	42.7	45.9	66.6	85.5	100.2
meas.		8531		57.0	43.0	41.2	58.2	80.1	94.8

* REPRODUCED BY PERMISSION OF DR. ROBERT McCLATCHEY[1]

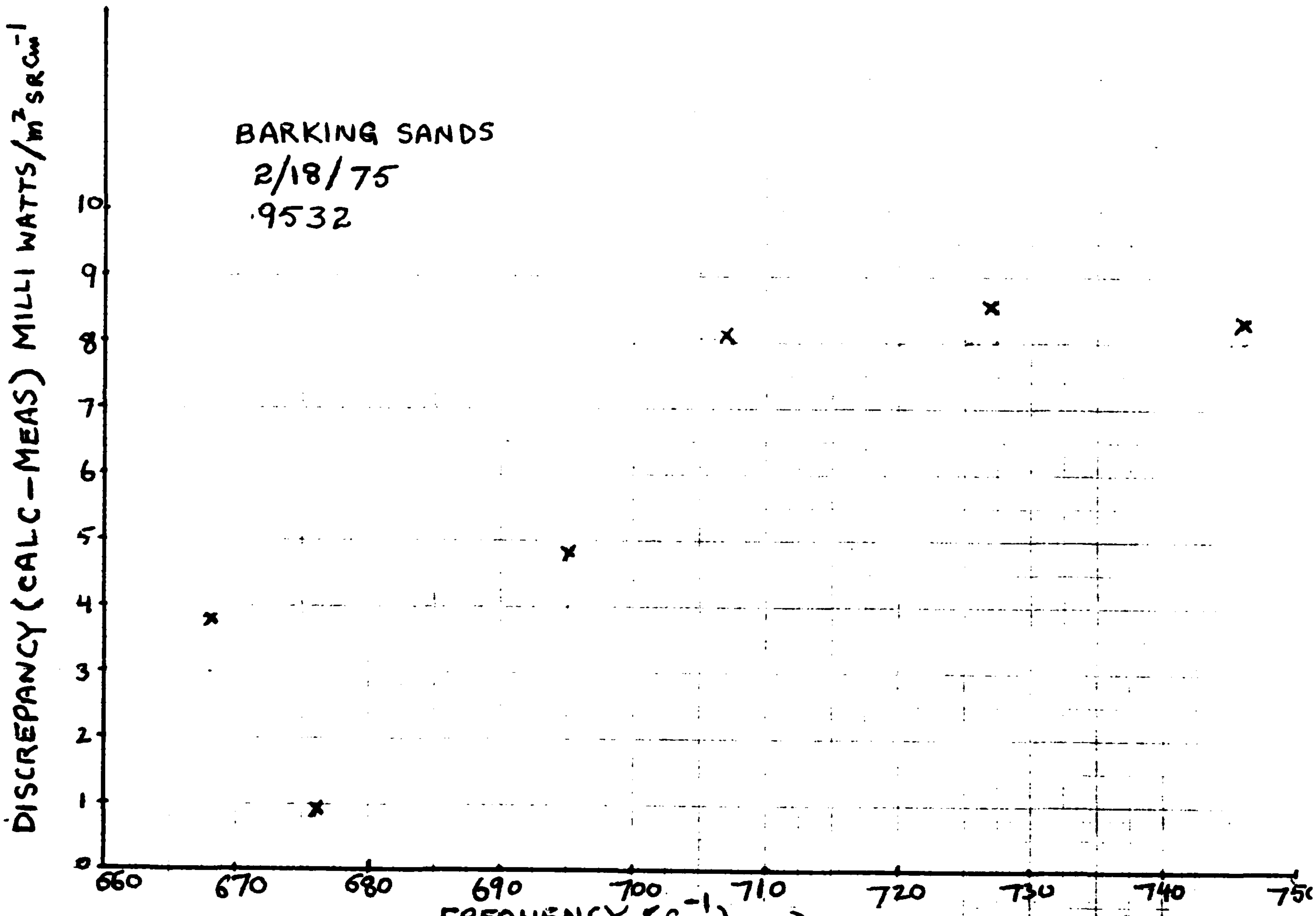

FIG. 1 EXAMPLE OF DISCREPANCY VS FREQUENCY (c.f Ref 1)

where $J_\nu(T(x))$ for the black body is the Planck distribution given by

$$J_\nu(T(x)) = \frac{h\nu^3}{4\pi^3 c^2}\left(e^{\frac{h\nu}{kT(x)}} - 1\right)^{-1}$$

Here $T(x)$ is the local temperature, ν is the frequency of radiation, c is the speed of light, h is Planck's constant and k is the Boltzmann's constant. If one introduces Schwarzschild's[3] assumption of "radiative equilibrium", which requires that the temperature distribution be considered time-independent and that all the heat transport be by radiation, then that would imply that the net energy transport across any plane perpendicular to the z-axis (altitude coordinate) must be constant:

$$\frac{\partial}{\partial z} F_\nu(z) = 0$$

where $F_\nu(z)$ is the next flux given by

$$F_\nu(z) = \frac{1}{\pi}\int_{-1}^{1} d\mu\, \mu\, I_\nu(\mu, z)$$

Here μ is the cosine of the angle between z -axis and the unit vector along the direction of the radiation flow. Clearly, the condition of radiative equilibrium is equivalent to saying that the net divergence of the energy flux is zero in any infinitesimal volume and all processes absorption and emission of the radiation are "localized" within that volume. As a result, there is no net transport of the radiation and the entire system remains in the localized state. On a closer examination one would then conclude that the radiative equilibrium condition would tend to overestimate calculations of the radiance and impose possible systematic errors.

As a final remark, we state that as yet no firm conclusions have been arrived at to explain or account for the discrepancy between the calculated and observed values of the radiance. Much further work is required. However, in this report we point out one possible path and write the appropriate relations for the case when the source function for the medium deviates from the black body function.

II. OBJECTIVES

Objectives of this project were:

(1) To analyze the discrepancies between the calculated and observed values of the radiance obtained from the Defense Meteorogical Satellite.

(2) To attempt to explain the discrepancies by recognizing the appropriate emission term which would be different from the black body function.

(3) To construct an appropriate radiative transfer model by relinguishing the assumptions of L.T.E and radiative equilibrium.

The objective described in paragraph (1) was readily fullfilled by the data provided by Dr. McClatchey[1] as reported by him in 1976. Objective (2) has been partially fullfilled and is reported here. Objective (3) will be matter of future investigation.

III. ANALYSIS OF THE DISCREPANCY

Consider the equation of radiative transfer in the pressure coordinate:

$$\frac{1}{K_\nu}\frac{d}{dp} I_\nu(p) = I_\nu(p) - J_\nu(p) \tag{1}$$

where p is the atmospheric pressure, K_ν is the absorption coefficient in the units of the inverse pressure, $I_\nu(p)$ is the radiation intensity and $J_\nu(p)$ is the source function. If the pressure is measured with the reference at the top of the

2

atmosphere ($p=0$), then following Chandrasekhar's treatment, Eq. (1) takes the integral form given by

$$I_\nu(p) = K_\nu \int_p^{p_g} dp' \exp(-K_\nu(p'-p)) J_\nu(p') + J_\nu(p_g) \exp(-K_\nu p_g) \tag{2}$$

where p_g is the pressure at the ground level. It is convenient to translate the pressure coordinate in the integral on the right hand side and write

$$I_\nu(p) = K_\nu \int_0^{p_g - p} dp' \exp(-K_\nu p') J_\nu(p'+p) + J_\nu(p_g) \exp(-K_\nu p_g) \tag{3}$$

At the satellite altitudes $p \simeq 0$, so that we have

$$I_\nu(0) = K_\nu \int_0^{p_g} dp' \exp(-K_\nu p') J_\nu(p') + J_\nu(p_g) \exp(-K_\nu p_g) \tag{4}$$

where $I_\nu(0)$ is the measured value of the radiance.

Now let $B_\nu(p)$ be the source function corresponding to the black body and $I_\nu^{(B)}(0)$ the associated radiance. If we assume that the source function $J_\nu(p)$ is also a black body type for $P = Pg$ so that $J(Pg) = B_\nu(Pg)$ at ground level, then the radiance $I_\nu^{(B)}(0)$ will have a representation similar to Eq. (4):

$$I_\nu^{(B)}(0) = K_\nu \int_0^{P_g} dp' \exp(-K_\nu p') B_\nu(p') + J_\nu(P_g) \exp(-K_\nu P_g)$$

(5)

Since $I_\nu(0)$ is the measured value of the radiance and $I_\nu^{(B)}(0)$ is the calculated value then we may write the discrepancy, simply as

$$\delta I_\nu(0) = I_\nu^{(B)}(0) - I_\nu(0) \tag{6}$$

and treat $J_\nu(p)$ as a trial source function so that

$$\delta J_\nu(p) = B_\nu(p) - J_\nu(p) \tag{7}$$

is the variation of source function. The equation relating $\delta J_\nu(p)$ and $\delta I_\nu(0)$ is then obtained simply by subtracting Eq. (4) from Eq. (5). Keeping in mind that $J_\nu(Pg) = B_\nu(Pg)$ at the ground level we obtain

$$\delta I_\nu(0) = K_\nu \int_0^{P_g} dp \, \exp(-K_\nu p) \, \delta J_\nu(p) \tag{8}$$

For some frequencies we can write Eq. (8) with the upper limit Pg set equal to infinity due to the exponential term (the transmittence).

Thus, we have the relation

$$\delta I_\nu(0) = K_\nu \int_0^{\infty} dp \, \exp(-K_\nu p) \, \delta J_\nu(p) \tag{9}$$

From a purely mathematical point of view, the discrepancy $\delta I_\nu(o)$ is related to deviation $\delta J_\nu(P)$ from the black body emission formally by a Laplace-like transform. Since the relation (9) holds for the monochromatic case, it may be written in the homogeneous form:

$$\int_0^\infty dp \exp(-K_\nu p) \left[\delta I_\nu(o) - \delta J_\nu(p) \right] = 0 \tag{10}$$

A. DIRECT APPROXIMATION

Equation (10) is useful for making an estimate of the integrand in the square brackets by arbitrarily using the e-folding pressure i.e $P = K_\nu^{-1}$; call that as P*. If we use the delta function $\delta(p - p^*)$ for the transmittence, then

$$\delta I_\nu(o) = \delta J_\nu(p^*) \tag{11}$$

for each frequency window, and the deviation of the emission law from the black body type is directly calculable from the measured values of $I_\nu(o)$ (the radiance) via Eq. (7):

$$J_\nu(p^*) = B_\nu(p^*) - \delta I_\nu(o) \tag{12}$$

with $P^* = K_\nu^{-1}$. We shall expound upon the usefulness of Eq. (12) in Sec. IV.

Since the e-folding pressure (P*) is frequency dependent, there would be corresponding corrected emission laws $J_\nu(P^*)$. An attempt will be made to recognize a physical law that best describes $J_\nu(P^*)$. We must keep in mind that the estimate given by Eq. (11) is good on the average for all values of the pressure i.e $\delta J_\nu(P)$ is properly approximated by $\delta J_\nu(P^*)$. One should also note the extent of determinancy of the problem when a linear approximation of $\delta J(P)$ is made.

B. LINEAR APPROXIMATION

Let,

$$\delta J_\nu(P) = \delta J_\nu(P^*) + (P-P^*)\, \delta^{(1)} J_\nu(P^*) \tag{13}$$

where

$$\delta^{(1)} J_\nu(P^*) = \frac{d}{dP} \delta J_\nu(P) \Big|_{P=P^*}$$

and put this expansion in Eq. (9), then the result is

$$\delta I_\nu(0) = \delta J_\nu(P^*) + \left(\frac{1}{K_\nu} - P^*\right) \delta^{(1)} J_\nu(P^*) \tag{14}$$

If $P^* = K_\nu^{-1}$, then second term on the right hand side of Eq. (14) vanishes and the result is again (see Eq. (11)),

$$\delta I_\nu(0) = \delta J_\nu(K_\nu^{-1})$$

From expansion (13), we obtain

$$\delta J_\nu(P) = \delta I_\nu(0) + (P-P^*)\, \overset{(1)}{\delta} J_\nu(P^*) \tag{15}$$

It is clear that one point will not determine a line (in fact, it is obvious). However, we may take the advantage of the boundary condition at the ground level ($P=Pg$) where $\delta J_\nu(Pg) = 0$.

Use of this boundary condition in Eq. (15) yields

$$\overset{(1)}{\delta} J_\nu(P^*) = - \frac{\delta I_\nu(0)}{P_g - P^*}$$

so that at any pressure point we have

$$\delta J_\nu(P) = \delta I_\nu(0) - \frac{P-P^*}{P_g - P^*}\, \delta I_\nu(0)$$

or

$$\delta J_\nu(P) = \frac{P_g - P}{P_g - P^*}\, \delta I_\nu(0) \tag{16}$$

C. GENERAL APPROXIMATION

Up to this point the problem of estimating $\delta J_\nu(P)$ is determinate for the linear approximation and for the monochromatic case. For expansions of higher order of the Taylor series form

$$\delta J_\nu(P) = \sum_{n=0}^{N} \frac{(P-P^*)^n}{n!} \overset{(n)}{\delta} J_\nu(P^*) \tag{17}$$

two points obviously will not suffice to determine all the expansion coefficients $\delta^{(n)} J_\nu(P^*)$. For one thing, at the top of the atmosphere the assumption of L.T.E. is totally absurd. On the other hand, if we assume that below some reasonable altitude, the L.T.E. approximation is sufficiently good so that $\delta J_\nu(P) = 0$ for $P \geqslant P_B$, where P_B is the reference pressure above which L.T.E. is assumed to be valid, then substitution of expansion (17) in the integrand of Eq. (9) yields

$$\delta I_\nu(0) = \sum_{n=0}^{N} \overset{(n)}{\delta} J_\nu(P^*)(-P^*)^n \sum_{\ell=0}^{n} \frac{(-1)^\ell}{(P^* K_\nu)^\ell (n-\ell)!} \tag{18}$$

If we again choose $P^* = K_\nu^{-1}$, then Eq. (18) reduces to

$$\delta I_\nu(0) = \sum_{n=0}^{N} \overset{(n)}{\delta} J_\nu(K_\nu^{-1}) \left(-\frac{1}{K_\nu}\right)^n a_n \tag{19}$$

where a_n are the universal numbers

$$a_n = \sum_{\ell=0}^{n} \frac{(-1)^\ell}{(n-\ell)!} \tag{20}$$

D. QUADRATIC APPROXIMATION

For N = 2, Eq. (19) yields

$$\delta I_\nu(0) = \delta J_\nu(P^*) + \frac{P^{*2}}{2} \delta^{(2)} J_\nu(P^*) \tag{21}$$

where $P^* = k_\nu^{-1}$ and we have noted that $a_0 = 1$, $a_1 = 0$ and $a_2 = \frac{1}{2}$ (see definition (20) for a_n). If we solve Eq. (21) for the second derivative $\delta^{(2)} J_\nu(P^*)$, then we have

$$\delta^{(2)} J_\nu(P^*) = \frac{2}{P^{*2}} \left[\delta I_\nu(0) - \delta J_\nu(P^*) \right] \tag{22}$$

For N = 2, if we eliminate the second derivative in the expansion (17) by using Eq. (22), we obtain

$$\delta J_\nu(P) = \delta J_\nu(P^*) \left[1 - \left(\frac{P-P^*}{P^*} \right)^2 \right] + (P-P^*)\, \delta^{(1)} J_\nu(P^*) + \left(\frac{P-P^*}{P^*} \right)^2 \delta I_\nu(0) \tag{23}$$

Choosing the pressure points at $P = P_B$ (above which L.T.E. is assumed valid) and $P = Pg$ where $\delta \mathcal{J}_\nu(P) = 0$, Eq. (23) gives us

$$\delta J_\nu(P^*) \left[1 - \left(\frac{P_B - P^*}{P^*}\right)^2\right] + (P_B - P^*) \delta^{(1)} J_\nu(P^*) = -\left(\frac{P_B - P^*}{P^*}\right)^2 \delta I_\nu(0) \tag{24-1}$$

$$\delta J_\nu(P^*) \left[1 - \left(\frac{P_g - P^*}{P^*}\right)^2\right] + (P_g - P^*) \delta^{(1)} J_\nu(P^*) = -\left(\frac{P_g - P^*}{P^*}\right)^2 \delta I_\nu(0) \tag{24-2}$$

We may solve Eqs. (24-1,2) for $\delta J_\nu(P^*)$ and $\delta^{(1)} J_\nu(P^*)$ and use Eq. (22) to find the second derivative $\delta^{(2)} J_\nu(P^*)$. Then all the coefficients in expansion (23) for $\delta J_\nu(P)$ are determined.

Due to time limitation, a complete analysis of this kind could not be carried out. However, we remark that the procedure adopted here looks promising. In particular, for arbitrary N, only the numerical calculations will reveal the usefulness of the procedure. Furthermore, we have considered the monochromatic case. In practice, one averages over the frequency windows, which will accordingly dictate the choice of P* in the expansion (17) for $\delta J_\nu(P)$ and corresponding relation (18) to the measurement $\delta I_\nu(0)$ of the differences in the radiance. The averaging is rather straightforward. If we assume that δJ_ν varies very slowly with frequency, then

Eq. (18), when averaged over the frequency with the appropriate filter function, gives us,

$$\langle \delta I_\nu(0) \rangle = \sum_{n=0}^{N} \delta J_\nu^{(n)}(p^*)(-p^*)^n \sum_{\ell=0}^{n} \frac{(-1)^\ell}{(p^*)^\ell (n-\ell)!} \left\langle \frac{1}{k_\nu^\ell} \right\rangle \tag{25}$$

IV. RECOMMENDATIONS

It is worthwhile to pursue the reasons for descrepancy between the measured and the calculated values of the radiance and possibly discover the appropriate source function which appears to be different from the black body function.

So far we have presented a purely mathematical procedure for constructing an appropriate source function to bring the calculated values of radiances to agree with the measured values. Nothing has been said about how that relates to the determination of a temperature profile. The nature of that problem is highly nonlinear, as can be seen by considering the source function given by Eq. (12). The nonlinearity is not removed even for the case when $\delta I_\nu(0) = 0$. However, as a simple example let us hypothesize that Eq. (12) holds for all pressures and examine the consequences which result, as a possible first iteration, in the determination of the temperature. Thus, let us say that the source function is generally given by

$$J_\nu(p) = B_\nu(p) - \delta I_\nu(0) \tag{26}$$

This source function can be used to recompute the radiance leaving the atmosphere and the results compared with the satellite measurements. If we consider this as the first iteration in solution of the transfer equation, then the question of convergence needs to be studied. It may give rise to the possibility of using higher order terms in the Taylor series expansion and repeat the process of the source function. Overall, our approach may find use in establishing a source function distribution consistent with a set of satellite measurements. Further study is required to see if this is possible and to understand the physical mechanism(s) responsible for giving rise to the source function determined in this way.

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FINAL REPORT

A HEURISTIC MODEL OF AIR FORCE MAINTENANCE PERFORMANCE

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Date:	August 1979
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A HEURISTIC MODEL OF AIR FORCE MAINTENANCE PERFORMANCE

by

William D. Kane, Jr., Ph.D.

ABSTRACT

The economic and political pressures on defense spending have Air Force managers seeking ways to fulfill mission requirements at lower costs. Since a substantial proportion of the defense budget is spent on maintenance, increases in efficiency in this area have a strong payoff potential. This effort was designed to produce a model of Air Force maintenance with which a larger effort to research maintenance performance would begin. The model was to be one which would lend itself to changes over time due to feedback from ongoing research. The original intent has been realized and a systems thinking model of individual maintenance performance has been developed up to the testing stage. The uniqueness of the model stems from its inverted approach as it focuses on optimizing individual outcomes by displaying the organization as inputs to the individual. The technician is the throughput stage within which the individual exerts effort and displays coping behaviors. The output stage is system performance in two dimensions--effectiveness and efficiency.

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I. INTRODUCTION

As economic and political pressures generate increased levels of debate and concern about our defense budget, military managers are being forced to examine alternatives for reducing costs. One of our national objectives has always been to maintain an adequate military posture. However, recent events have increased the emphasis on maintaining that posture at the lowest cost. The arguments at the center of the national debate on defense spending do not stem from the intent of either of the above statements, but rather from the attempts to provide operational definitions of those statements. The disagreement comes when we try to agree upon what is meant by "adequate posture," how much or how little that should cost, and what the relationships are between the two.

In response to these external forces, the Air Force continues to examine its activities and is seeking ways to fulfill its mission while at the same time reducing its spending. As over one-third of the defense budget is spent on the delivery of logistics support, some attention has focused on this area.[1] Logistics support is not only costly, it is imperative that it provide operational weapons systems on demand or the money originally spent will have been to no avail; and, in the worst case, national safety will be jeopardized.

Without getting into a discussion over the definition of logistics, I think we can agree that the maintenance of the weapons systems designed, procured, and supplied by the rest of logistics system is in and of itself a critical function. It is not only a critical function but in this era of rapidly rising manpower costs it is an expensive one.[2] Owens et al. estimated that in 1974 \$1.5 billion was spent by the Air Force on avionics maintenance alone. Add the costs of organizational and field maintenance (no data available) to that figure, include the impact of inflation, and we can conservatively speculate that the annual cost of Air Force aircraft maintenance in 1979 will exceed \$5 billion. If we then bring into the equation the cost of missile maintenance and civil engineering maintenance, we are talking about costs far in excess of \$5 billion; and the potential for savings through improved maintenance is considerable.

The military has traditionally been labor intensive and has solved maintenance problems by adding manpower. When manpower was cheap, that might have been a viable alternative; but given current manpower costs, that alternative has lost its attractiveness. Mistakes made elsewhere in the system eventually end up in maintenance as it is the end of the sequential chain. However, budget cuts which resulted in manpower reductions have eliminated the slack at the end of the sequential chain; and now when cumulated mistakes are passed along the chain to maintenance, their response capability to additional demands is extremely limited and the impact is more obvious and painful. Therefore, if you cannot add more people, one of the other obvious alternatives is to get more out of the people you have. Investigating what "getting more out of the people you have" means and how you might go about that is a project of current Air Force interest and is the focus of this paper.

This study looks at what the military and others have done to improve maintenance performance, considers those findings in a systemic format, derives implicit assumptions, presents a model that displays a systems approach to individual maintenance performance, and suggests how one would go about validating that model. This model is at the descriptive stage, which must come before the quantitative stage, but contains at least the basic factors necessary to study the problem of increasing maintenance performance while decreasing costs.

II. OBJECTIVE OF THE RESEARCH EFFORT

The objective of this effort is fairly straightforward. As part of a contractual obligation, the Air Force Human Resources Laboratory is required to provide a model of the Air Force maintenance system to the winning contractor within 30 days of the contract award. The approximately 39-month-long contract is designed to investigate what needs to be investigated to establish a long-term Air Force maintenance research plan. As I had 20 years of experience in Air Force maintenance and six years of academic work studying organizational behavior, they asked me if I would attempt to develop the model for the contract. The AFHRL people were not sure what the model should look like or what the inputs should be, but they were certain that what they had seen was not what they wanted.

As can be seen in the rest of the paper, the objective was accomplished. The staff at AFHRL has been briefed on the herein contained model and the rationale behind it and have been complimentary in their remarks about it. It is the overwhelming consensus that the model approximates the system; it is an actionable model whereby research can clear up weak areas; and, most important of all, it makes obvious the heretofore neglected interaction variables.

III. LITERATURE REVIEW

A review of the pertinent literature reveals that the Air Force has been investigating maintenance performance, in one guise or another and at various levels of support, since the early 1950s. Modrick compiled an annotated bibliography (two volumes) of a number of maintenance studies accomplished between 1953 and 1958 that focused on task accomplishment as well as troubleshooting.[3] However, no summary or generalizable recommendations were given across the material and the individual pieces are just that--pieces. This isolated, piecemeal studying of task performance typifies the research done in this area, and it is difficult to tell the efforts of the 1970s from those of the 1950s. The findings continue to cite the same problems of technical data and test equipment misuse, poor troubleshooting or fault isolation techniques, and general maintenance ineptitude, by the researcher's criteria.

One line of research that has resulted in action to solve previously identified problems is the ongoing research in the improvement of technical data. This work has focused first on task analysis and then on the development of detailed job guides to simplify task accomplishment. The work of Foley[4] and Shriver and Foley[5] has focused on making the maintenance task easier to accomplish which can reduce costs in two ways--reduced training and increased individual output. The work on detailed job aids seems wellgrounded; it can and has produced positive results; and it is one way of maintaining output, reducing costs, and dealing with the declining quality of the maintenance force. However, while this line of research is necessary, it is not, in and of itself, sufficient; it addresses only one part of a multi-part problem. As Foley[6] points out, by addressing only the technical data issue and ignoring the concomitant issues of selection, training, promotion, and complex technology, you may be creating more problems that you are solving.

A third line of inquiry into maintenance performance has been the use of systems theory or systems thinking to surround and grasp the complexities of the maintenance system. Much of this work focused on developing hard measures of maintenance performance, at various levels of analysis, and none of the efforts were particularly successful because the scope of what they were attempting was beyond their resources. Additionally, these studies typically begin by attempting to quantify that which has yet to be described or analyzed.

Myers et al.[7] developed a plan for investigating human resources problems; but, as field level maintenance personnel quickly point out, they already have a heck of a list of problems. They would welcome assistance but in eliminating problems, not in expanding the list.

While some of systems genre studies did not adequately use systems thinking, three studies were encountered that did. The first was done by Hoisman and Daitch.[8] They reviewed the literature relating personnel performance to systems effectiveness criteria and began by being concerned with a classification scheme and interdependent relationships.

> The heart of the analytic problem, in our context, appears to be the classificatory framework of the analytic scheme more than the operations involved. That is, the nature of the categories into which the system is to be analyzed and partialled is more critical to the needs of the standard derivation methods than the procedures used to make the analysis, although both are important.[9]

They reviewed over 400 reports and concluded that approximately 50 reports were usable for their purposes, and the overwhelming majority of them were technical reports rather than articles from academic journals. The conclusion of their review was:

> . . . as clearly borne out in the literature, there are few workable techniques for assessing personnel performance within the context of system effectiveness, and equally important, it has been only within the past few years that some of the critical factors comprising effectiveness have been identified. Put another way, unless one can identify the necessary and sufficient dimensions of system effectiveness, i.e., what constitutes system success, one cannot begin to relate personnel performance to system criteria. Until the two problems, assessing personnel performance and identifying system requirements, are satisfactorily solved, useful and meaningful techniques of relating one to the other are obviously precluded.[10]

Unfortunately, Hoisman's and Daitch's conclusions are almost as appropo to 1979 as they were to 1964. Their conclusions make a contribution to the model developed later in this paper.

The second study encountered that utilized systems thinking to examine maintenance was done by Drake et al.[11] This study is the best of its kind encountered and the study's subject was a comparison of Army and civilian helicopter maintenance. Drake et al. realized that the maintenance function is embedded in a larger, overall system and that inputs from that system could have significant influence on maintenance activities. Their stated purpose " . . . was to explore those organizational factors, emphasizing incentive structures, which might be responsible for the high costs of the military maintenance operations."[12] They proceeded on the assumption that "a major reason for the previous lack of payoff in maintenance research and development is a relative neglect of important organizational factors."[13] Drake et al. were aware of the organizational behavior literature (see their bibliography, p. 6-1, 6-7) that treats many of the organizational factors that were thought to impinge on individual behavior and utilized it to develop their perspective. Their study is unique in three aspects: it considers individual performance as embedded in a larger system; it uses the organizational behavior literature as a basis for investigating that system; and methodologically it uses an interesting technique. "The technique used in this project for collecting comparative data is that of investigative reporting . . . . In essence, the approach is to 'pick up a string and follow it to its ends.'"[14]

Drake's et al.'s study also comes to an interesting conclusion.

> The results of our analysis indicate that the biggest payoff in improving military maintenance effectiveness and efficiency is not in introducing additional incentives but rather in reducing or eliminating the existing disincentives. Military mechanics like being mechanics and want to spend more time at it.[15]

Their conclusion indicates that the problem is not necessarily at the individual level of analysis but rather that part of the problem might be the organization in which the individual is imbedded. The individual level of analysis is necessary, but to embrace factors that meet the conditions of being both necessary and sufficient, one must also include the organizational levels of analysis and the interaction between them. This study has major implications for the model developed later in this chapter.

The third study found to be useful in developing this paper's model is one done by Rice.[16] The study, or series of studies, is operations research oriented and as such neglects human factors issues, at least at the individual level of analysis. However, it does provide some insight on the system side of what will eventually be a systems thinking-organization-human factors integration.

In the portion of his study discussing the weapons system acquisition process, Rice paints a scenario that relates directly to maintenance issues.

> Present practices seem to reflect the conviction that:
>
> 1. Mission requirements can be firmly specified before development begins or technological capabilities are verified;
> 2. Important configuration decisions and technical specifications can be based reliably on design studies and analyses alone; and
> 3. Subsequent development of the system will encounter no problems severe enough to upset cost and schedule projections. Unfortunately, there is little historical basis for such faith and considerable evidence that the policy it engenders is not very successful. In one set of 24 systems of the 1960s that embodied these assumptions, typical outcomes included cost growth (in constant dollars) averaging 40 to 80 percent, schedule slippages, and performance shortfalls.[17]

Rice goes on to state that the same analysis for the 1970's systems does not demonstrate much improvement.

The above scenario has strong implications for the Air Force maintenance system because when that weapon system arrives on the flight-line or at the silo the maintenance technician is going to have to make it work. If the acquisition process was in error concerning the above variables, why should it be assumed that the estimates of maintainability and reliability are any more accurate? One might seriously question whether the maintainability, including human factors, ever received indepth consideration at all. The aggregation across time of the above errors will end up in the technician's lap and will add substantially to maintenance costs. Rice comments further.

> An almost inevitable consequence is a long (and costly) modification phase needed because there was insufficient opportunity to detect technical and operational defects, correct them, and incorporate changes before substantial numbers of production articles were delivered. During this phase, which may last for several years, system performance (including operational availability) typically falls well below the desired (or "required") levels. The result is not only that the forces must rely on systems that do not perform as expected (and, presumably, as necessary), but also that the DOD incurs high, post-acquisition costs.[18]

Some of the high, post-acquisition costs that Rice refers to are maintenance costs, presumably direct maintenance costs. However, along with direct maintenance costs go a number of human factor costs. What might the impact be of a weapons system that required extensive modification over a several year period on motivation, training, frustration, maintenance scheduling, operations, confidence in the maintenance system, parts availability, and a host of other variables? The answer to that question is that the costs are high, but no one currently knows exactly how high. I think we can say, with some degree of confidence, that the impact on maintenance performance would be substantial and that the technician's "poor performance" (high cost) would be due to circumstances largely beyond his/her control.

Rice's presentation is important to the development of this model because it again illustrates how false cause-effect relationships can develop if you forget that human factors are imbedded in a larger system. The purpose of the model in this paper is to systemically portray the Air Force maintenance system and to show how individual performance is impacted by that system.

This review is not a detailed coverage of all of the material examined; space does not permit that. It is a general brush across several literatures both within and without the defense community. It includes some of the human factors literature, some systems analysis, and a little of the combination of the two. Hopefully, this review has set the stage for the introduction of this paper's heuristic model, which will be developed in the next section.

IV. DEVELOPMENT OF THE MODEL

This model takes as its focus the output (performance) of the human system in Air Force maintenance. The model will emphasize a systemic approach as it looks across, as well as within, subsystems to see how they impact on that most important aspect of any organization--getting the product out the door. As mentioned earlier, some of the previous research has been well done and it has been necessary. However, in and of itself that research will provide only partial answers and may even produce dysfunctional results because it ignores critical interactions with other parts of the system in which the technician is imbedded. This heuristic model avoids that pitfall and addresses factors that are necessary and/or sufficient. The model also recognizes the possibility of multiple interactions and the importance that interactance has for the outcomes of the system (performance). The rest of this section will develop the rationale of the model, present the model, and suggest how the model can be utilized to investigate Air Force maintenance performance.

The Air Force is generally viewed as a traditional hierarchy, and the research on the maintenance function has focused on the bottom of that hierarchy, but as viewed from the top (see Figure 1). The Air Force hierarchy is representative of what is called a tall organizational structure, many vertical divisions, and as such probably has the attendant characteristics.[19] Tall organizational structures are characterized as having one-way communication, narrow spans of control, many layers of supervision, and centralized authority. These characteristics contribute to the misperception by those at the top of the organization as to what is going on at the bottom and vice versa. Those at the top assume that their world is representative of the bottom and draw conclusions accordingly. In reviewing the available literature, I have identified nine implicit assumptions that originate from organizational misperceptions. These nine implicit assumptions are:

TRADITIONAL HEIRARCHY

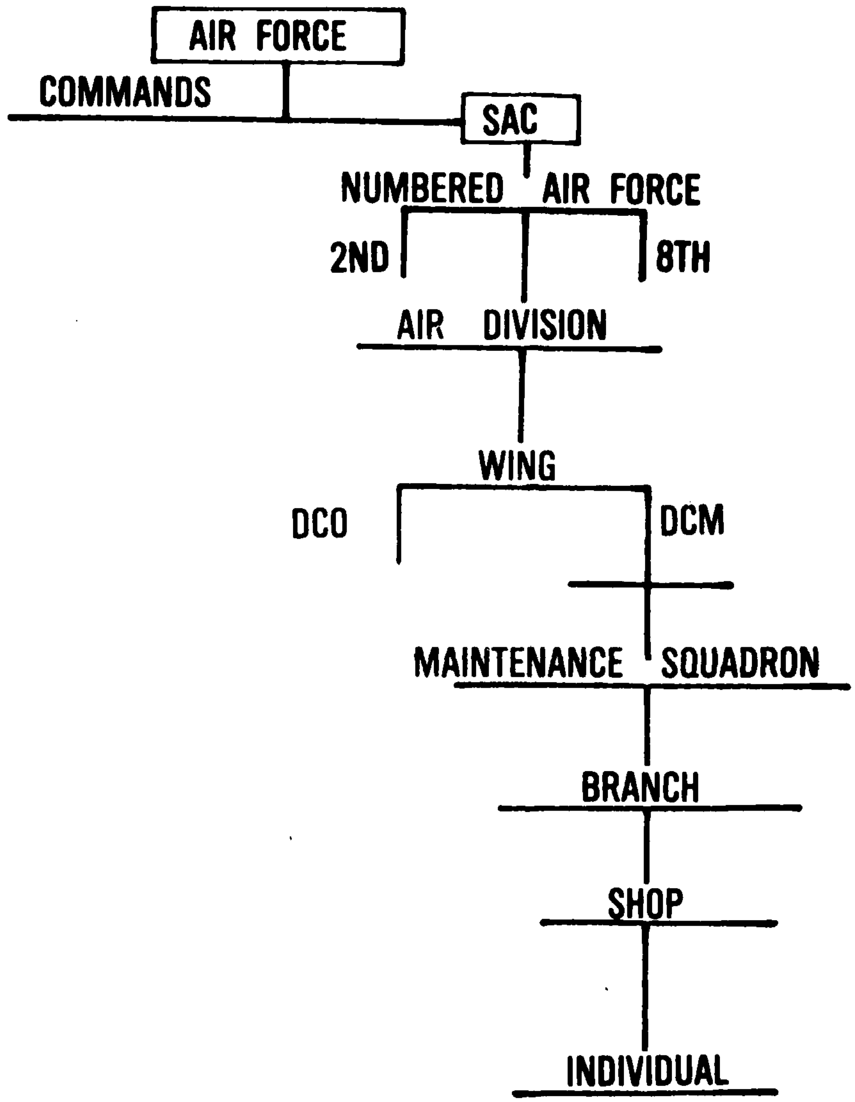

FIGURE 1

1. The individual technician controls the majority of the variance in the maintenance situation.
2. The amount of variance in performance (output) is fixed.
3. A simple solution exists.
4. The "system" knows what it is doing.
5. Maintenance is a discrete, rather than a continuous, event.
6. Meanings are the same across levels of analysis.
7. All maintenance is aircraft oriented (in all of the documentation reviewed, neither missile maintenance nor civil engineering maintenance was ever mentioned).
8. The current focus on discrete maintenance tasks is both necessary and sufficient to study performance, and
9. The maintenance world is a simple world.

I believe that all nine of these implicit assumptions are false and that they stem from organizational misperceptions. Also, since they are deducible from the research, they are inherent in the research; and if the research is based on false assumptions, there is reason to suspect the research. As mentioned earlier, some of the research is quite sound but its scope is narrow and may actually have dysfunctional results outside of its parameters. Therefore, since most of the research on Air Force maintenance performance has been influenced by the biases of those viewing the system from the top, some new way of viewing old problems needs to be generated.

In grappling with the idea of viewing old problems in new ways, the question arose as to how we could optimize individual performance. One answer to that is that for research purposes we could seek to optimize individual output. If we think of Air Force maintenance as a system comprised of some number of subsystems and if we invert that system and display the subsystems as supporting the individual, we could begin to think about the inputs necessary to optimize individual output (see Figure 2). By dividing the Air Force system into six subsystems--

AN INVERTED VIEW

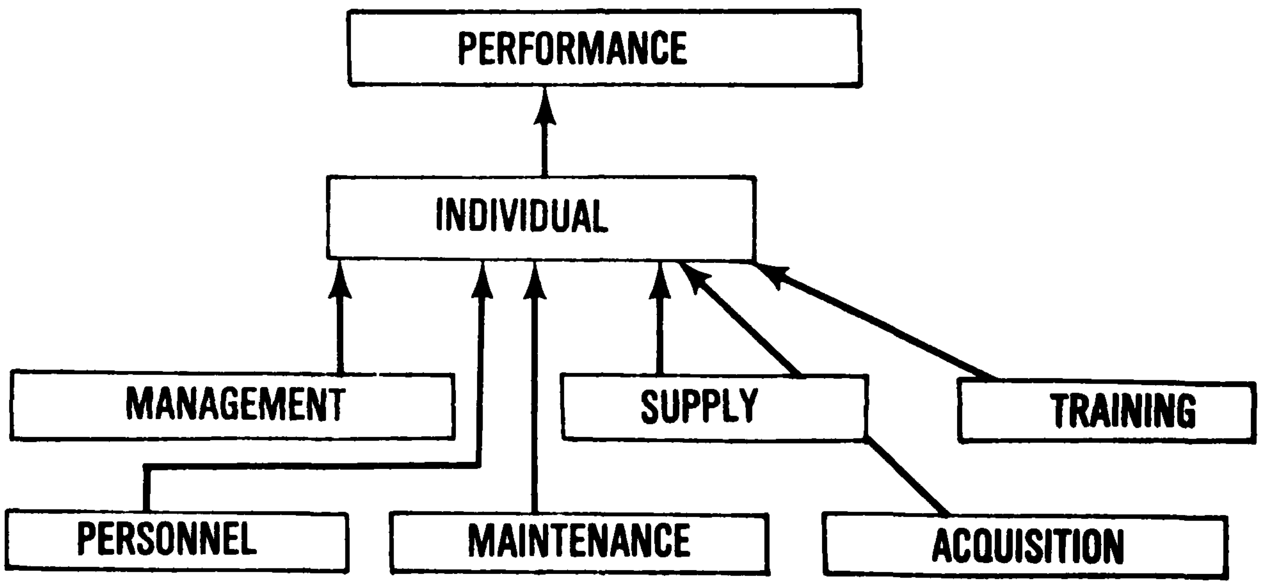

FIGURE 2

management, supply, training, personnel, maintenance, and acquisition--pertinent to maintenance and displaying them as system inputs to an individual whose output is maintenance performance, we have a way to systematically investigate maintenance performance. It also becomes obvious that the subsystems are not independent, but interdependent, as shown in Figure 3 (see Figure 3). The exact extent of the interdependence is a research question, perhaps the central research question, and it has not been investigated or acknowledged until now.

Studying this inverted model of performance begins to make obvious some of the previously identified implicit assumptions. Space precludes a detailed derivation of all nine, but a derivation of several will serve as an example.

Once we view the subsystems as inputs, it becomes much more problematic as to the amount of variance the technician controls and whether or not it is fixed. If we set the subsystems up on a time line from time zero to time n and think about the things that can go wrong (they can also go correctly) before they get to the individual, we can then argue that the technician may control a small amount of output variance and that variance may differ over time (see Figure 4). Examination of Figure 4 indicates that errors could aggregate over time and also between subsystems. The accumulated error terminates at the individual technician where he or she can also contribute error. However, the important point is that mistakes made five or six years ago in the acquisition process, in the assigning or training process, in management policies, in the structure of the maintenance system itself, may all combine algebraically to dominate the variance that appears to exist at the technician level. The technician may be competent, committed, and hard-working, may be performing above the 100 percent mark, and the resultant system performance may still be poor (high cost). Past research has implicitly assumed that the technician controlled all of the variance and that it was fixed, which is the reason why what good

SUBSYSTEM INTERACTION

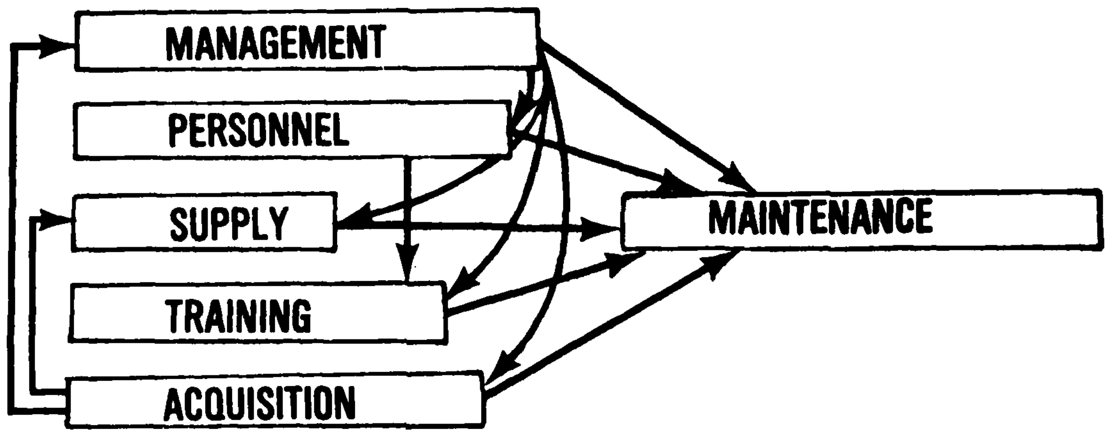

FIGURE 3

INDIVIDUAL CONTROL OF VARIANCE?

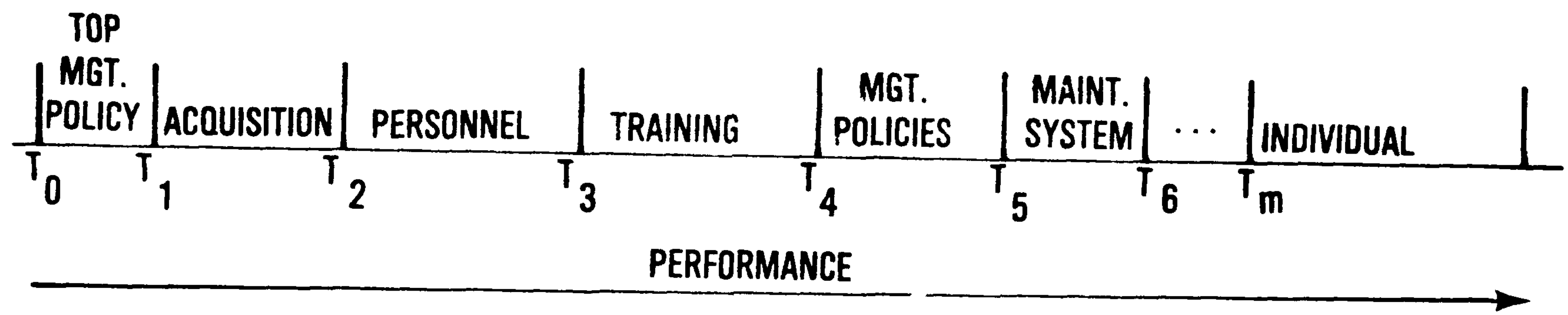

FIGURE 4

research that has been done is necessary, but it has not been sufficient. The assumed cause-effect relationships were much too simple.

Another implicit assumption that must be clarified is that meanings are the same across levels of analysis (Number 6). When this research began, it appeared that one of the first issues that must be dealt with was the definition of performance. However, it soon became apparent that the major issue was one of level of analysis rather than definition because multiple definitions of performance exist depending upon where you sit in the hierarchy. A wing commander's definition of performance is not the same as a flight line technician's; but they are both "right," they exist simultaneously, and they both have reference to this research. If you look at performance by level of analysis, or where you sit in the hierarchy, you can develop a series of definitions of performance as follows.

1. Individual. Completed task or narrow series of tasks that leads to proper functioning of one system in one aircraft or missile.
2. Shop. Completion of a number of tasks by some number of individuals that leads to the proper functioning of a number of the same system (i.e., Doppler).
3. Branch. Completion of many tasks by many people that leads to the proper functioning of a grouping of related systems (i.e., Doppler, Bomb Nav).
4. Squadron. Completion of a large number of tasks that leads to the proper functioning of a large grouping of systems (i.e., AMS, FMS, OMS).
5. Wing. Completion of a large number of tasks that leads to the proper functioning of some number of an end item weapons system (i.e., F-16, Minuteman, B-52).

This line of reasoning can continue up the hierarchy and derive definitions for Division, Numbered Air Force, and Major Command. The point is that they are all somewhat different, they are all "right," they are simultaneously ongoing, and they all have impact on the system output--performance. Instead of only a definitional issue, we have a definitional issue by level of analysis; the meaning of terms varies depending upon where you sit in the hierarchy. If you are at the major command level using that level's definition of performance, it is no wonder that you would have difficulty improving performance at the technician's level; you are talking about different things. Once you realize, however, that they are different and need to be measured differently, some of the difficulty diminishes. Looking above at the various definitions by level of analysis, you can see that performance (defined later) can be measured but it must always be stated at which level you are measuring.

The remainder of the implicit assumptions are fairly obvious from the above discussion and from viewing Figures 2, 3, and 4. We will further pursue model development based upon an inverted system whereby the previously identified six subsystems provide input to the individual who does something (throughput) that results in a completed task (output). At the same time, we will continue to be cognizant of the falsity of the implied assumptions.

This model will focus on the individual technician as a system having inputs, throughputs, and outputs. As discussed earlier, it is an inverted system whereby, for research purposes, the intent is to optimally view what is required to increase individual performance. Model development will proceed from the input stage to the throughput stage through the output stage. The completed model can be seen in Figure 5, and you need to keep in mind that the model is still in the descriptive phase and as yet no effort has been initiated to quantify any variables or interactions.

The breakdown of the maintenance system into six subsystems and the inversion of the system so that those subsystems provide input to the individual is revealing, but not specifically. A more precise view of what the inputs are is needed. By asking what are all the things that a technician needs to get the job done, a categorization of the inputs to the individual emerges. The input portion of the model contains four categorizations--ability, equipment, motivation, and support--within which all of the factors that bear on individual task performance can be expressed. (This model is artificially constrained at the boundaries of the Air Force and primarily bounded by those areas pertinent to maintenance.) At the same time, we can plug one or more of the six subsystems into each of the four categories and begin to display some of the

A HEURISTIC MODEL OF AIR FORCE MAINTENANCE PERFORMANCE

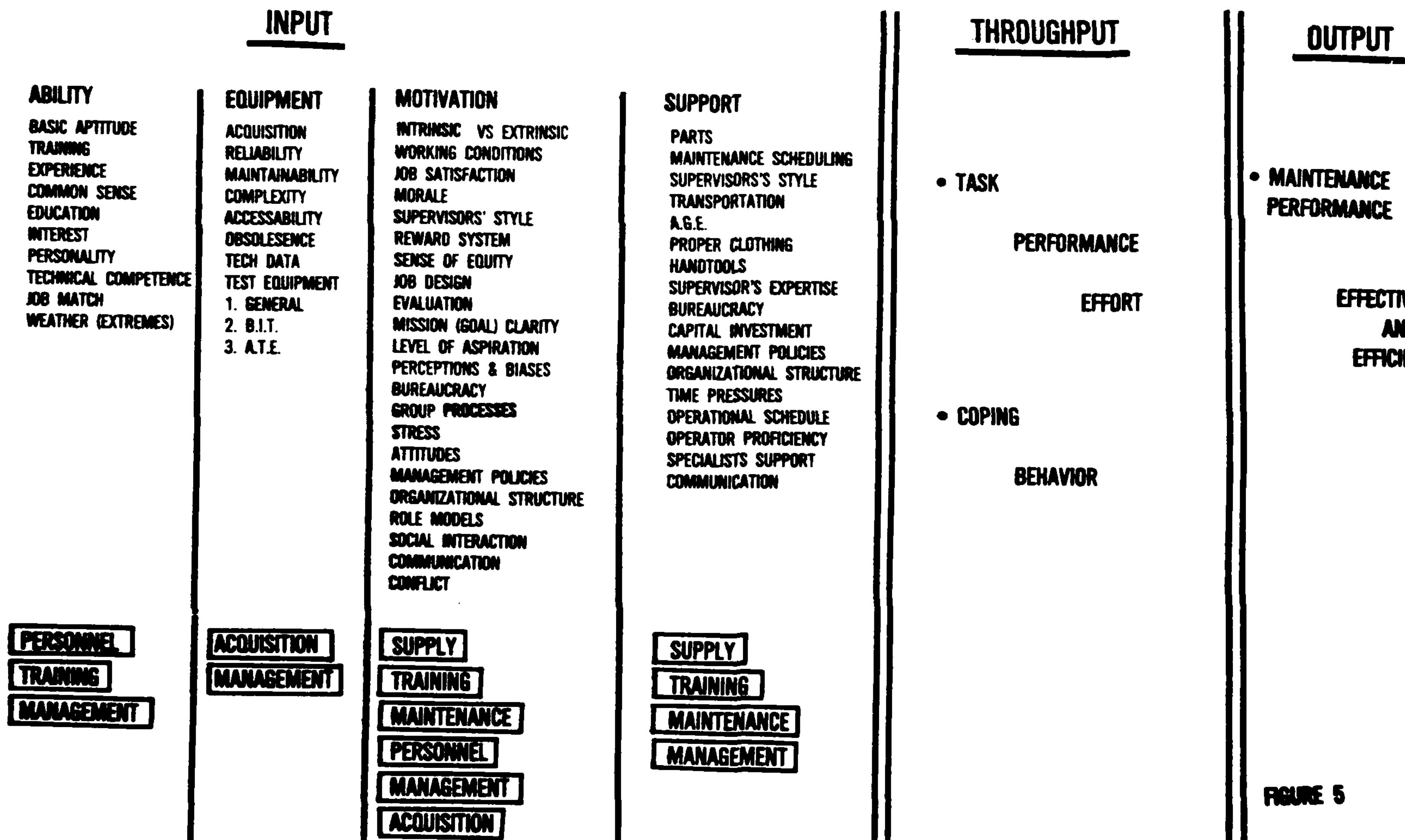

FIGURE 5

interlocking interdependencies. Under each of the four input categories is a list of variables, derived from the literatures and experience, that are thought to be crucial to successful task performance (output). As can be seen by examining Figure 5, this list is far more inclusive than previous research has indicated. There has been research focused on technical data, on reward systems, and on training, but not on most of the other variables indicated, and particularly not on the interactions between them. This list is not intended to be all inclusive and indeed probably contains variables that are less significant than others. What should or should not be included is a research question, but what is important is that now there is a framework within which to conduct this research. (A definition of each of the variables in the four categories can be found in Appendix A.) That framework also makes it very apparent that research that ignores the interactance, both vertical and horizontal, while necessary, cannot be necessary and sufficient.

Realizing that boundary drawing around and within models is somewhat arbitrary, we next proceed to the throughput stage of the model. Once the individual has the minimum inputs to the task, he or she then exerts effort to accomplish some specific task or relatively narrow series of tasks. The technician engages in some type of behavior that is more or less appropriate to successful accomplishment of the task at hand. How appropriate and successful that behavior is depends upon the technician, to some extent, and also upon the various inputs provided by the six subsystems. If the subsystems' inputs are inappropriate, so will be the behavior. The technician may be poorly trained, lazy, or incompetent, but it is also possible that the weapons system has a faulty design, there are not enough spare parts available, he or she is being overtaxed due to poor scheduling, or a host of other explanations. Explanations for poor performance (inappropriate behavior, high cost) have, in the past, focused only on the individual. This model makes it apparent that to correctly analyze the inappropriate behavior the individual and the system within which he or she is imbedded must be examined.

There is at least one other facet of the throughput stage of the model and it is badly neglected. None of the research reviewed mentioned how technicians cope with the variety of distractions in the maintenance environment. Most of the past research was done in controlled or partially controlled environments where efforts were made to exclude environmental distractions. The task was taken out of its context. As the technician goes about his or her daily business, the environmental distractions (the contextual variables) become an inherent part of the maintenance task. Along with technical competence and effort and all of the other inputs, the technician needs to develop a concomitant set of behaviors that helps him or her to structure the environment so that task completion is possible. Distractions such as faulty test equipment, no crew chief, no power, crowded working area, wrong tech data, need for spare parts, newly discovered system malfunctions, poor peer relations, and others are intimately related and crucial to task success. I would hypothesize that: (1) technicians spend more time coping with distractions than on direct maintenance and (2) those technicians who have developed the most adaptive coping behaviors are those that will be perceived as the "best" technicians. This area of maintenance research has been totally neglected, and it is crucial to improved performance that that neglect be eliminated.

The conclusion of the model is the output stage, and here is where we finally come to grips with what we mean by performance. Performance is the output of the system we have modeled, and it is at the individual level of analysis, as previously stated. It is not inappropriate to discuss system performance at the individual level of analysis if you remember the discussion about different, simultaneous, ongoing definitions of performance. Connell and Wollam[20] queried a range of managers at all levels of command as to their definitions of effectiveness. "All levels of command chose 'providing aircraft as required to meet mission requirements' as the most important measure of maintenance effectiveness out of the eight choices."[21] This commonly accepted definition of effectiveness will be used here as the performance measure, and performance is stated as <u>providing an operational weapons system on demand</u>. Using the definitions of performance discussed earlier by levels of analysis provides a way of measuring the output (performance) at several levels of analysis, including the individual level. After all, an F-15 ready for takeoff is really an aggregate of successful individual task accomplishments, and it is possible to break that aggregate down into its component parts.

Performance here, however, has two dimensions--effectiveness and efficiency. What we have talked about so far is effectiveness, or whether or not we have achieved our goal.[22] Efficiency is the ratio of inputs to outputs utilized to accomplish that goal. Not only is goal accomplishment considered (effectiveness), but the cost of that goal accomplishment (efficiency) is also important. For this model then, performance is defined in terms of effectiveness--providing an operational weapons system on demand--and efficiency--providing an operational weapons system on demand at the lowest cost concurrent with mission requirements.

The military has traditionally emphasized effectiveness and ignored efficiency. Economic and political forces are making it necessary to think more in terms of efficiency but without loss of effectiveness. Like any well-run organization, the Air Force wants to maintain or improve performance, but at the same time it seeks to lower the cost of doing business. The whole intent of this model and subsequent research is to maintain effectiveness while increasing efficiency.

The measure or measures of cost will eventually have to be worked out. Costs could be stated in dollars, manhours, mean time between failure, numbers of bodies assigned, some composite of these, and others, or, more than likely, in a variety of terms depending on the purpose or level of analysis. What to use for cost measures is another research question but one that is relatively straightforward compared to some of the other questions raised herein.

As indicated in the title of this model, A HEURISTIC MODEL OF AIR FORCE MAINTENANCE PERFORMANCE, this is not a static or quantified model. This model is a dynamic learning vehicle which should be improved and modified, as appropriate, as research provides new insights into the issues. This model is the beginning that hopefully will assist in defining research that will maintain the Air Force's effectiveness while improving its efficiency. It is too early in the research to be seeking quantification. Quantification in organizational research should come after some initial variables have been identified and some thought given to the interactions that might exist between them. I think this model has done that.

V. RECOMMENDATIONS

The model herein described and the rationale of its development provides researchers and managers with a somewhat different perspective on increased performance. Not only is it a different perspective, it is an actionable one; this model can be put to work. The first step is to do a sensitivity analysis on the variables in the four categories in the input stage of the model. Much of the sensitivity analysis in the motivation category could be done from the behavioral science literature with some assessment of its applicability to Air Force maintenance. The variables in the ability, equipment, and support categories, while present in most organizations, will probably have different cognitive content or labeling for various types of organizations. Sensitivity analysis of these variables will require field work to include questionnaires, interviews, and observation to determine which are important, which are not important, and which might be missing.

The second step is to determine how the categories of inputs individually impact on the technician behavior that results in maintenance performance. As this is not a laboratory study, you cannot manipulate one independent variable at a time and observe what happens to the dependent variable while controlling all other independent variables. Therefore, interviewing and observing methodologies appear to be the most appropriate for assessing tentative cause-effect relationships. Also, the methodology used by Drake et al. that they termed an approximation of investigative reporting might prove useful here. It will be important to develop some idea of the impact of a single category on performance because the next step will be quite difficult.

The third step that I would recommend will be the toughest one to implement and carry on to a satisfactory conclusion and will literally push the state of the art. The third step will be to determine what the interactions are between the four categories and the impact of those interactions on behavior and performance. Without further research, I do not know how this could be accomplished, and it is the most critical aspect of the model. I know about multi-variate analysis and operations research, but nothing I am aware of exists whereby you can take it off the shelf and plug in the numbers. This aspect of the model has the highest potential for payoff if it is done correctly. However, it will also incur the highest cost.

The fourth step, observing technician behavior, can be done in conjunction with step two. The fourth step would be to analyze the throughput section of the model as technicians exert effort and engage in behaviors designed to conclude assigned tasks. Methodologies appropriate to step two would be utilized here.

The fifth and final step is to analyze the output stage of the model. The output stage is performance which was the impetus for this project originally. Using the bi-levels analysis definitions of performance discussed above, measurement of goal performance (effectiveness) even at the individual level of analysis should be comparatively easy. Effectiveness measures of quantity and quality are available in the Maintenance Data Collection System (at the local level, not aggregated data), in the Quality Control Program, and in systems performance records.

Measurement of the efficiency dimension of performance will be more difficult. Since we are interested in the cost per unit of goal accomplishment, some measure of what that cost is and in what unit or units it should be expressed will have to be developed. Some possible units are dollars, manhours, number of bodies assigned, or, more likely, some index designed for this purpose.

These five recommendations are advanced with the awareness that each of them is a major research question. However, the research must start somewhere and based on the literature reviewed, my experience, and the model developed herein, I think these beginning steps are realistic. The model is developed as a heuristic device and is designed to change as research provides new insights. It would be interesting to observe the evolutionary development of the model.

Two areas of research have come to mind that lay outside the scope of this project. One has been previously mentioned, coping behavior, and the other is a just-realized implicit assumption. There is a lot of literature on coping behavior, but none of the research I am aware of focuses on the positive aspects of coping behavior engaged in to enhance task accomplishment. I believe that investigation of technician's coping behavior developed to contend with environmental events could prove quite enlightening.

The second research issue that is a recently realized implicit assumption is that "all maintenance occurs in a peacetime environment." Not one piece of material reviewed (all unclassified) even mentioned the implications for maintenance performance of wartime conditions. The reason for the existence of the maintenance force is to maintain equipment during peace time training so as to either avoid war through preparedness or fight it if necessary. However, no research addresses what is hypothetically a totally different environment with different outcomes and different costs. Research into this area could have significant results for overall defense posture.

VI. CONCLUSION

The conclusion of this project is really a beginning rather than an ending. The purpose of this research was to develop a model that would outline an approach to an intensive 39-month " . . . development of a comprehensive, integrated research and development program to improve the performance of individuals, groups, and organizations responsible for maintaining aircraft and missile weapon systems" (from statement of work). I think this model and the rationale behind it provide a sound base from which to begin the larger effort. The model was intentionally labeled a heuristic one because at this stage that is all it can be, a learning device that will change as feedback is received from ongoing research. The investigators in the larger effort have a challenging task before them. Some of what they are attempting has never been done well in a small system and probably has never been attempted in a system this large. However, if we are to successfully manage large systems--goal accomplishment at reduced cost--we first need to understand the dynamics of them. The field testing of this model should have a positive impact on the maintenance of Air Force weapons systems and also contribute to doing that at a lower cost. That would not be a modest outcome.

This piece of research contains at least four novel approaches. The first and probably least noticeable is the integration of several literatures, my professional training, and my background experience so that a testable model of a large, complex system resulted. When the model is tested, the results, when and if applied to the system, will be both necessary <u>and</u> sufficient; and solutions can be developed for problems that will not cause even more serious dysfunctions. The second novel approach is the inversion of the system, which then makes it possible to view the individual in an optimal state with the organizational subsystems displayed as inputs. I think this is the major contribution and the one around which the whole project centered. The third approach was making obvious the implicit assumptions utilized in previous research. The visibility of these heretofore invisible assumptions helped to clarify where the gaps existed and also suggested how they might be filled. The fourth and last novel approach was the verbalization of the implicit assumptions that individual technicians had control over whatever variance might exist in the maintenance situation. I think, argumentatively at least, that that notion has been strongly challenged.

This concludes this study's investigation into Air Force maintenance performance. If managers are to grasp the intricacies of complex systems, they must realize that viewing them and behaving as if the systems are simple ones is inadequate for the task; complex issues cannot be resolved using simplistic approaches. As Weick comments:

> If a simple process is applied to complicated data, then only a small portion of that data will be registered, attended to, and made unequivocal. Most of the input will remain untouched and will remain a puzzle to people concerning what is up and why they are unable to manage it.[23]

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APPENDIX A

Definitions of Input Variables by Category

ABILITY

1. Basic aptitude	The inherent potential to perform tasks in one area or another as measured by the Airman Classification Test.
2. Training	The formal or on-the-job training that closely focuses on assigned or to be assigned tasks.
3. Experience	The sum total of cognitions that can be applied in some manner to an individual's Air Force Job.
4. Common sense	The inherent knack of doing the right thing at the right time.
5. Education	Formal years of schooling such as high school and college as they pertain to needed Air Force skills.
6. Interest	How well the individual attends to and is concerned with environmental events.
7. Personality	The totality of an individual's emergent tendencies to act or behave . . . or to act on, interact with, perceive, react to, or otherwise meaningfully influence or experience his environment (from Webster's Third New International Dictionary, 1967).
8. Technical competence	The sum total of an individual's ability, training, education, and experience, and how he or she applies it.
9. Job match	The personnel function of pairing the Air Force's needs and the individual's abilities and desires.

10. Weather	Climatic conditions at the extremes that inhibit performance.

EQUIPMENT

1. Acquisition	The process by which Air Force equipment is designed, developed, and brought into the active inventory.
2. Reliability	The probability that a part, component, subassembly, assembly, subsystem, or system will perform for a specified interval under stated conditions with no malfunction or degradation that requires corrective maintenance actions. Also Mean Time Between Failure (MTBF). (from AF Regulation 80-5, "Reliability and Maintainability Programs for Systems, Subsystems, Equipment, and Munitions," 2 July 1973).
3. Maintainability	A characteristic of design and installation expressed as the probability that an item will be restored to a specified condition within a given period of time when the maintenance is performed using prescribed procedures and resources. Also Mean Time to Repair (MTR). (from AFR 80-5 as cited above).
4. Accessibility	The physical availability of installed equipment. The degree of effort that must be exerted just to "get at" the equipment.
5. Obsolescence	How far behind the "state of the art" the equipment is that is being maintained. This has implications for spare parts availability, test equipment, and management interest.

6.	Technical data	The officially published information on how to test and inspect, remove and replace, service, maintain, and operate specific pieces of equipment.
7.	Test equipment	Those devices used to aid in the troubleshooting, calibration, alignment, and repair of weapons systems components. Two examples are voltmeters and oscilloscopes.
	a. General	Test equipment that has multipurpose uses and that can be used across a number of systems.
	b. B.I.T.	Built-In Test Equipment where the test equipment is an integral part of the system.
	c. A.T.E.	Automatic Test Equipment where the technician connects the equipment component to a test set and then follows a relatively simple program while the test set evaluates the component. The technician does not need to know how to perform the test; he or she only needs to know how to follow the test initiation and advance program. The test set determines if the unit passes or fails.
8.	Complexity	The varied and overlapping interrelations within and between equipment that require an expanded range and depth of knowledge in order to understand and cope with system functioning and malfunctioning.

MOTIVATION

1. Intrinsic vs. extrinsic	Intrinsic motivation derives from factors within an individual (self-motivating) while external motivation derives from factors outside of the individual (other motivated).
2. Working conditions	The environment within which the work task is imbedded such as temperature, noise level, hazard, monotony-boredom, closeness of supervision, and geographical location.
3. Job satisfaction	An attitude or set of attitudes that, when expressed, convey how the worker "feels" about his or her job or about various facets of the job.
4. Morale	A more organizationally oriented, rather than task oriented, feeling expressing the individual's assessment of the worth of belonging to the group.
5. Supervisor's style	The subordinates' assessment of how the supervisor manages his or her total task-people obligations. In research terms, not subordinates', it is generally expressed at or somewhere between extremes of authoritarian and permissive.
6. Reward system	The organizationally controlled system whereby promotion, pay increases, increased responsibility, and other perquisites are administered.

7.	Sense of equity	The sense of fairness that pervades the workplace based upon the perceived rewards that are attributed to perceived effort.
8.	Job design	The restructuring of jobs to increase a job's intrinsic motivators.
9.	Evaluation	The assessment, by whatever means, of an individual's performance by his or her supervisor.
10.	Mission (goal) clarity	The extent to which organizational members understand the organization's central purpose and how their efforts contribute to that purpose.
11.	Level of aspiration	The relative strength and direction of individuals' desire to improve their lot or to have and seek to achieve ambitions.
12.	Perceptions and biases	The view of the world, and events in it, that an individual has based upon his or her total life experiences.
13.	Bureaucracy	The negative connotation of imposed structure whereby rules and regulations become ends in themselves rather than means to ends. What becomes important is following the rules, not getting the job done.
14.	Group processes	The ongoing activities and relationships within groups that lead to cohesiveness, belonging, conflict, cooperation, leadership, followership, and group output.
15.	Stress	The strain and tension experienced by an individual that is generated by occurrences within or associated with the workplace.

16.	Attitudes	Affective or emotional opinions about persons, places, and things that stem from, and/or interact with, perceptions and attributions.
17.	Management policy	The decision rules established by the officially appointed hierarchy that are used to process organizational events.
18.	Organizational structure	Organizational components such as size, division of labor, technology, formalization, complexity, and hierarchy (centralization or decentralization of power).
19.	Role models	Those others whom individuals would like to emulate and who they attempt to pattern their behavior after.
20.	Social interaction	The opportunity to participate in group processes within the workplace and also other activities that carry over from the workplace such as going to lunch and participating in sports.
21.	Communication	Both the formal and informal messages that are received and transmitted in a variety of formats and media up, down, across, and within hierarchial groups and individuals. The message content may pertain to a variety of functions such as task, motivation, interpersonal, intragroup, intergroup, or organizational.

22. Conflict

That which results from disagreements over allocation of scarce resources, interpersonal squabbles, differences on how to handle critical events, and any organizational event or process that results basically in a win or lose situation.

SUPPORT

1. Parts	The availability of spare parts to repair components or larger end items of weapons systems or support equipment.
2. Maintenance scheduling	The production scheduling of technicians, support equipment, and weapons systems with the intent of producing an integrated effort with minimal interference from conflicting requirements.
3. Supervisor's style	The subordinates' assessment of how the supervisor manages his or her total task-people obligations. In research terms, not subordinates', it is generally expressed as at or somewhere between the extremes of authoritarian and permissive.
4. Transportation	The availability and timeliness of the means to commute to and from the maintenance shop to a work location such as the flight line or a missile silo.
5. A.G.E.	Aerospace Ground Equipment--the powered and non-powered equipment necessary to support maintenance on aircraft and missiles such as power units, air conditioners, maintenance stands, special transportation dollies, air carts, tractors, tow bars, and air compressors.
6. Proper clothing	The provision of garments to protect the technician from extremes of weather and toxic environments.

7.	Hand tools	The smaller implements necessary to complete assigned tasks such as wrenches, screwdrivers, sockets, pliers, and wire cutters.
8.	Supervisor's expertise	The capability of the immediate supervisor to provide competent technical direction and instruction.
9.	Bureaucracy	The negative connotation of imposed structure whereby rules and regulations become ends in themselves rather than means to ends. What becomes important is following the rules, not getting the job done.
10.	Capital investment	The amount of dollars invested in maintenance equipment to support maintenance. Maintenance has been traditionally labor intensive and for all intents and purposes still is. One way to increase output is to increase capital investment.
11.	Management policies	The decision rules established by the the officially appointed hierarchy that are used to process organizational events.
12.	Organizational structure	Organizational components such as size, division of labor, technology, formalization, complexity, and hierarchy (centralization or decentralization of power).
13.	Time pressure	The cumulative resultant of scheduling and mission requirements whereby technicians are squeezed to complete more tasks in less time to the point of diminishing return.

14.	Operational schedule	For aircraft it is the flying schedule of training missions that produces unscheduled demands on the maintenance system. Silo missiles generate far fewer unscheduled maintenance demands and most actions are done on a scheduled basis.
15.	Operator proficiency	How well the system operator, generally different from the maintenance technician, understands and operates the equipment. The operator's expertise also influences how well system malfunctions are explained or described to the maintenance system and how often "normal" system operation is reported as abnormal.
16.	Specialists' support	Situations arise where one technician needs the assistance of a different kind of technician in order to proceed with or conclude his or her work. One example would be an electronics technician who required the services of a sheet metal technician to remove some stripped screws from an access cover before he or she could proceed.
17.	Communication	Both the formal and informal messages that are received and transmitted in a variety of formats and media up, down, across, and within hierarchial groups and individuals. The message content may pertain to a variety of functions such as task, motivation, interpersonal, intragroup, intergroup, or organizational.

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FINAL REPORT

AN EVALUATION OF A METHOD FOR ASSESSING AIRCRAFT STRUCTURAL DAMAGE FROM MULTIPLE FRAGMENT IMPACT

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Date: November 27, 1979

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AN EVALUATION OF A METHOD FOR ASSESSING AIRCRAFT STRUCTURAL DAMAGE FROM MULTIPLE FRAGMENT IMPACT

by

A. E. Kelly

ABSTRACT

The finite element method was proposed for the evaluation of residual strength of damaged aircraft structures (1). Implementation of the method was by the general purpose finite element program NASTRAN. In this report the analysis procedure is reviewed and the method for structural analysis is evaluated. Results from the analysis of a 14-bar truss may be used as a guide to evaluate the accuracy of the method to predict the response of damaged structures. Recommendations are made for the use of the differential or geometric stiffness method for structural analysis, as well as the development of test data to validate the methodology.

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I. INTRODUCTION:

Aircraft components which have been damaged by missile or projectile fragments experience a reduction in strength. The residual strength of the structure may not be sufficient to sustain the applied loads, resulting in structural failure. On the other hand, the structure may be found suitable for the applied loads, but a reduction of stiffness may result in excessive deflection which would cause the structure to fail to perform under flight conditions. The prediction of the residual strength and stiffness of damaged structures is essential for the evaluation of aircraft survivability/vulnerability. In this work, a method (1) for predicting the residual strength and stiffness of damaged structures will be reviewed. The method was developed by the Air Force Armament Laboratory (AFATL), Eglin Air Force Base, and utilizes conventional structural finite element methodology with the general purpose program NASTRAN.

The finite element method is well-suited to the analysis of damaged structures. It provides a high degree of flexibility for structural idealization. The size and type of element may be selected to define complex structural detail or damage. NASTRAN is a logical program for the implementation of the method because of its accessibility and use by both government agencies and the aerospace industry.

The objective of this work is to review the AFATL methodology for the analysis of damaged structures. The method employs static analysis to predict the response of the damaged structures. The static analysis is compared with the transient response due to sudden member failure. While the study is performed on a simple truss structure, the results may be extrapolated to the more complex aircraft structure.

Finally, recommendations are made for the application of NASTRAN for the evaluation of structural damage and for future research to verify the methodology.

II. AFATL STRUCTURAL VULNERABILITY METHODOLOGY

The aircraft structure is represented by an assembly of finite elements (2). The wing structure of Reference (1) required more than 1800 elements. The finite elements must be selected so that the structure is suitably modeled. A damage case is imposed on the structure by the removal and modification of the elements. When necessary, the structural idealization will be changed by inserting or deleting node points and elements.

The modified structure is analyzed to determine static stresses and deflections. The original flight load, less load eliminated because of local damaged skin, is applied to the modified structure. The static response of the damaged structure may be significantly different from that of the undamaged structure, especially if primary structural members are damaged. However, for highly redundant aircraft structures, the effect of damage is often difficult to predict without a structural analysis which includes the possible load paths for internal forces.

Following the static analysis, the element stresses are investigated for possible structural failure. The criterion for element failure is a function of element location. For those adjacent to the damaged area, failure is assumed if the calculated element stress exceeds the yield strength of the material. Elements not in contact with the damaged area must be subjected to stresses which exceed the ultimate strength of the material for failure to occur.

The rationale for this criterion is related to the effect of the fragment or projectile damage. It is assumed that cracks in the damaged material may extend up to and across element boundaries, and failure under these conditions may be propagated at the level of the material yield strength. Material unaffected by structural damage is assumed to fail when the stress exceeds the ultimate strength of the material.

Of the elements found to have stresses exceeding the limiting values noted above, the element which exhibited the greatest stress in excess of the limiting value was removed. It is important that only one element is removed. While the analysis may indicate the failure of a group of elements, only the member having the largest stress excess is removed.

The modified structure is again analyzed to determine static deflections and stresses. The process is repeated until deflections become excessive or element failure is no longer observed.

III. DISCUSSION OF AFATL METHODOLOGY

There are several important assumptions inherent to this methodology. First, the effect of fragment or projectile impact is to penetrate or remove material. Energy of the particle is not transmitted to the structure to cause a change in velocity or vibration. While this assumption may be accurate for multiple fragment impact from missile warheads, the impact of large projectile warheads with the wing structure may produce measurable structural vibration.

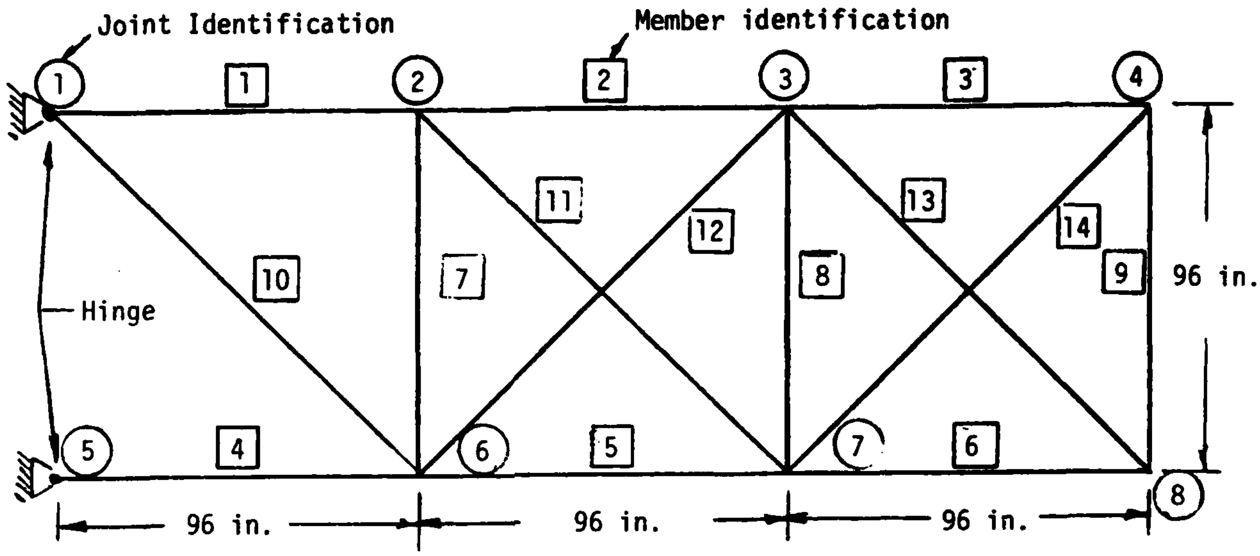
A second assumption, to be investigated in the following section, is that the sudden failure or removal of structural material may be evaluated by static analysis of the remaining structure. To evaluate this assumption, the transient response of a simple structure subjected to sustained loading and sudden element failure will be studied.

Finally, the method of analysis permits only small structural displacements. While this assumption is usually suitable for the analysis of undamaged aircraft structures, the effect of structural damage usually produces large local displacements which are not properly represented in the element force equations. This results in estimated deflections which may exceed the actual displacements and calculated element forces which are less than the actual values.

To overcome this problem, a first order approximation for nonlinear large deflection equations is available in NASTRAN. The differential stiffness or geometric stiffness (2) rigid format provides an iterative solution of the nonlinear, deflection-dependent equilibrium equations. If the static analysis is suitable for the prediction of the structural response, the analyst would be advised to use the NASTRAN differential stiffness method to predict deflections and stresses. Furthermore, the effect of large compressive stresses on element buckling, a problem neglected by small deflection theory, may be approximated by the differential stiffness method. In an earlier study of the effect of damage on structural response (3), significant panel buckling was noted in the vicinity of the damage on the compression surface of the wing.

IV. EVALUATION OF STATIC RESPONSE ASSUMPTION

As mentioned earlier, a finite element model of a complex aircraft structure may require over 1000 elements and an equal number of degrees-of-freedom. Structural models of this size require significant computation for either static or dynamic analysis. To evaluate the effect of damage on the transient response of a structure, the 14-bar truss shown in Figure 1 will be analyzed. While the structure has only 12 degrees-of-freedom, results from this study may be extended to the behavior of complex structures having many more degrees-of-freedom and comparable relative damage.



Member Area: Chord, 4 in.^{2}
Vertical, 2.5 in.^{2}
Diagonal, 1.5 in.^{2}

Modulus of Elasticity: 3×10^7 lb/in.^{2}
Density: 0.28 slugs/in.^{3}

FIGURE 1 - EXAMPLE PROBLEM, 14-BAR TRUSS

The structure is loaded by downward vertical forces of 50 kips at joints 2, 3, and 4, and will be analyzed by the method described in section II, and by a transient analysis in which member 12 is suddenly removed. From a static analysis of the undamaged structure, it was found that 6.6 percent of the structure's strain energy is stored in member 12. This is comparable to energy stored in the damaged structure studied in Reference (1).

Results of the analysis are shown in Table 1. Static analysis was performed on the structure following the removal of member 12. Both the maximum deflection and the amplitude of the vibration due to the sudden elimination of member 12 are shown as the transient response in Table 1.

TABLE 1. VERTICAL DEFLECTION OF JOINTS (INCHES)

Joint	Static	Transient Maximum	Transient Vibration	Percent Difference
2	-2.61	-3.18	(0.71)	-17.9
6	-2.29	-3.08	(0.79)	-25.6
3	-4.89	-5.91	(2.05)	-17.3
7	-4.78	-5.70	(1.83)	-16.1
4	-6.21	-7.34	(2.10)	-15.4
8	-6.22	-7.37	(2.13)	-15.6

The variation in the element forces are shown in Table 2.

TABLE 2. MEMBER FORCES (KIPS)

Member	Static	Transient Maximum	Transient Minimum
1	300.0	454.0	136.2
2	100.0	260.7	-48.3
3	57.9	147.9	-1.1
4	-600.0	-479.0	-753.0
5	-300.0	-188.1	-370.4
6	-42.1	25.0	-108.4
7	-250.0	-138.1	-354.5
8	-92.1	11.0	-153.0
9	7.9	36.6	-0.9
10	424.3	522.6	319.5
11	282.8	439.1	124.6
13	59.6	125.7	-6.3
14	-81.9	-11.9	-137.1

Results shown in Tables 1 and 2 indicate that the existing method for predicting residual strength underestimates the response of the damaged structure. The force in member 4 due to transient analysis is 20 percent greater than predicted by static analysis.

Although the structure studied for this work does not represent an aircraft wing, the effect of the sudden removal of wing structural components would cause a similar response. However, the greater redundancy of the wing structure provides more load paths around the damaged area. On the other hand, it would not be unreasonable to expect similar results from damage in the vicinity of or to the primary wing structure.

V. RECOMMENDATIONS

The finite element method provides a valuable tool for the structural analysis of damaged aircraft components. It must be emphasized that the work described in this report focuses on the analysis of structures subjected to sustained loading, which may or may not be representative of aircraft flight loads. It was shown that the static analysis method for predicted response of damaged structures underestimates member forces and structural deformation. This has the effect of increasing the survivability (or decreasing the vulnerability) of the structure. The analyst must recognize this limitation when using the methodology reviewed by this report.

On the other hand, the use of the small displacement theory may overestimate structural deformation and underestimate member forces. However, if buckling of structural members is eminent, deflections may be underestimated. The use of differential or geometric stiffness will provide a more realistic prediction of the static response of damaged structures.

Finally, it is recommended that further research be performed to develop data to support the method of repeated static analysis to predict failure. The observation of a failure test of a structure would be valuable to validate the progressive structural failure predicted by the methodology.

Although aircraft structural failure is not a static process, to represent the structure for dynamic analysis to include element failure is beyond the scope of most general purpose finite element programs. Furthermore, it is questionable whether the cost of such an analysis is justified in view of the uncertainties related to the problem. The static anaysis techniques of the AFATL methodology provide an economically feasible solution for the residual strength analysis of damaged aircraft structures.

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FINAL REPORT

GROUNDWORK FOR OCULOMOTOR RESEARCH IN SIMULATORS

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GROUNDWORK FOR OCULOMOTOR RESEARCH IN SIMULATORS

by

Robert V. Kenyon, Ph.D.

ABSTRACT

Eye position and eye movement information reflect the processing of visual and vestibular information as well as higher cognitive processes in the human operator. Oculomotor behavior, such as that exhibited by experienced pilots, can aid researchers in understanding the human processing of various sensory inputs necessary to perform highly skilled motor coordination tasks. Few simulators currently possess the capability to record oculomotor information. This report concerns the development of this capability in the Williams AFB Advanced Simulator for Pilot Training (ASPT). Essential parameters to consider in augmenting simulator capabilities are outlined. Status on implementation of eye position recording system in the ASPT is reported.

ACKNOWLEDGEMENTS

The author wishes to thank the Air Force Systems Command, the Air Force Office of Scientific Research and the Southeastern Center for Electrical Engineering Education for providing this opportunity for research at the Human Resources Laboratory at Williams Air Force Base. I would especially like to thank Dr. Richard N. Miller for his efforts in assuring a pleasant and productive summer appointment. The research and technical staff at the Human Resources Laboratory are much appreciated for their support and informative inputs into my research. Dr. Robert Kellogg deserves special thanks for his outstanding efforts on my behalf to make my stay at Williams an enjoyable and productive research experience.

I. INTRODUCTION:

Eye movements are an important parameter when investigating the processing of information used in a motor coordination task such as flying. Eye movements refect a subject's processing and integration of information from both visual and vestibular sensory systems as well as higher cognitive processing.

The eye which has a small mass, is rotated in its orbit by six powerful pairs of reciprocally innervated muscles. This mismatch results in the lowest amount of motor force pattern smearing of any motor control system. Consequently, eye movement responses can be analysed for information on the nature of the motor control system characteristics as well as the interaction between motor control patterns from other sensory systems.

Eye movements are also essential for the visual system to aquire information about the visual environment. Although the visual field of view available on the retina at any one time is $\pm$ 80 degrees of visual angle, only a central area of about $\pm$ 1 degree of visual angle (the fovea) can resolve high spatial frequency information. This foveal area has a visual acuity of 20/20 or a resolution of 1 minute of arc. Therefore when the sharpest perception of an object is desired, the eye is rotated so that the image of the object is fixed at the fovea. Consequently, eye position in space indicates which objects in the field of view are of interest to the observer. This information would be beneficial in many experimental conditions. For example, knowledge of where a pilot is looking and for how long during intricate manual control tasks can provide objective information on the pilot's performance under various physical and psychological conditions. Scanning patterns recorded from skilled pilots in combat may be a means of transfering pilot skills to less experienced pilots.

Unfortunately, few research groups using simulators measure eye movements as part of their experimental protocol on pilot performance. A human factors research group sought to institute a program for routinely recording eye position of pilots while operating the simulator during various experimental conditions. This report will concern itself with the initiation of various aspects of eye movement research to this group's flight simulator and its use.

II. OBJECTIVES OF THE RESEARCH EFFORT

The objectives of this project were:

(1) to introduce eye movement research methods and concepts to the division personnel for the initiation of such research on flight simulators;

(2) to advise on the type of eye monitors that could be used in simulators and to evaluate the possible systems that may be purchased by the division for eye position monitoring;

(3) to become familiar with the capabilities and operations of the simulators available at this division so future experiments of mutual interest could be conducted.

Due to the brevity of my appointment and the absence of an operational eye monitoring system when project was initiated, formal research project using the simulators was not included in the objectives of this project.

III. THE CONTROL AND MEASUREMENT OF EYE MOVEMENTS

The division personnel had limited exposure to eye movement control systems and the various techniques used to record eye position. To remedy this situation a seminar covering the field of eye monitoring principles and techniques was given to the division. In addition, a second seminar dealt with the type of visual information used to control the eye. In the first seminar, eye movement methods from simple observation to the latest sophisticated methods using TV systems and computers were covered. The emphasis was placed on methods that would be amenable to the demands of simulator use. Possible improvements in several methods being considered for use in the simulator were discussed in these seminars. The subsequent seminar dealing with motor control of the eye surveyed the literature on information processing and the resultant control patterns measured by monitoring the eye. The seminar covered the four basic eye movement control systems: saccadic; smooth pursuit; fixational; and vergence systems. Within each system the specific stimuli that is processed by each was discussed with the related oculomotor response. Also the interactions and independence of each system were presented by example experiments.

The background material presented in the seminars were followed up by hands-on experience with two methods to monitor eye position with an analysis of the motor response recorded. The system most often used in this follow-up period was the photocell method marketed by Applied Sciences Laboratories (Model 2002). Using this device the division personnel were able to gain experience in the use of eye monitors, their advantages and limitations, as well as the source of artifacts and how to minimize their influence on the data. Personnel involved with this hands-on experience learned quickly how to obtain reliable recordings using this device. In the process, they also learned the various responses that can be expected from each system that controls the eye.

The second method, electro-oculography, could not be applied to measure eye movements of subjects since the necessary equipment to implement this technique was absent. Therefore, the experiments using this method were confined to testing different electrodes and amplifiers to implement this method. Division personnel received information and instruction on the proper amplifiers needed and the correct handling of the surface electrodes for proper operation.

IV. EVALUATION OF EYE MONITORS FOR SIMULATOR USE

Recording eye position in an aircraft simulator without undue constraints on the pilot is a challenging engineering problem. Eye monitoring methods that may be adapted for solution are: TV eye monitors and electro-oculography. Both systems were familiar in varying degrees to some division personnel. The eye movement technology seminar supplemented this knowledge for some personnel and introduced these methods to others. However, a description of the operating principles and their applications to an eye monitoring system do not in themselves enable a decision regarding which system is more suitable. Demonstrations of each device supplied the additional information necessary to make this decision.

Regarding the TV monitoring system, investigations showed that two systems were commercially available: the Applied Sciences Laboratories Eye-Trac Model 1998 and the Honeywell Oculometer. During related business in Boston I arranged a demonstration of the Applied Sciences Laboratories Eye-Trac System for myself and another member of the division. During this visit we were both able to obtain some hands-on experience using this device and to observe its performance and its limitations. During that same visit we also used the less sophisticated photo-cell system Model 2002 which was eventually purchased to introduce the division personnel to eye movements as mentioned in the above section. The purchase of this device was not meant for use in the simulator.

I also arranged for a demonstration of the Honeywell Oculometer and evaluated it in similar manner. Results from these two meetings showed that either device could operate well in the simulator.

Other questions which I addressed regarding these two systems included:

-- determining the level of support each system would require;

-- determining the reliability of each device; and

-- identifying sources of expertise on use of these devices in simulators.

Inquiries into support requirements showed a comparable level of support for each device was needed. Reliability and ease of use were also rated comparable. Regarding sources of expertise, a large research team at NASA, Langley, Virginia, was found to have been using the Honeywell system for several years. This group has amassed significant software and hardware adaptations to the original system. The Langley personnel have a number of years of experience in using the oculometer in simulator environments. Additionally, a group at Wright-Patterson AFB has just started to install an oculometer in the LAMARS device. The Langley personnel demonstrated willingness to share their knowledge with the Williams AFB group; Williams staff will likely visit the Langley laboratory. A comparably experienced group using the Eye-Trac in simulators was not found.

Electro-oculography is not as sophisticated a method of measuring eye position as is the TV systems just discussed. However, electro-oculography (EOG) is fast to prepare and easy to use. Unfortunately, EOG suffers from an unstable baseline and a high degree of noise within the bandpass of interest for eye movements. Recently, an improvement in electrode manufacturing the accompanying electrode paste has reduced the baseline drift so that short term experiments may be possible. An investigation into electrodes made by various manufacturers of surface electrodes resulted in testing an infant cardiac electrode for use in eye monitoring experiments. The tests on these electrodes showed some promise for use in the simuator but a complete study on their suitability was not possible due to the lack of the proper amplifiers,

V. FAMILIARZATION WITH SIMULATOR CAPABILITIES

Although the summer project contained no formal research on the simulators, the time was also used to familiarize myself with the various aspects of research conducted on the simulator. During this period I acquired a working knowledge of the simulator's capabilities as well as its engineering constraints. Discussions with technical support personnel facilitated my evaluation of the hardware; Software development and support personnel briefed me on the realistic capabilities of the Computer Image Generation system. My familiarization was greatly enhanced by opportunities to obtain several hours of simulator "flying time." This time enabled informal experimentation which in turn gave rise to ideas for future research.

VI. RECOMMENDATIONS

Selection of an appropriate integrated TV eye monitoring system for use in the simulator must be based on two key parameters:

-- familiarization of user groups with maintenance and operation of the system; and

-- existing software capabilities for data manipulation and reduction.

Williams AFB personnel are largely unfamiliar with the installation and maintenance of eye position recording systems. Although both Applied Sciences Laboratories and Honeywell provide limited software support, existing in-house capabilities are heavily burdened and additional software development in the area of data reduction may prove difficult given current levels of resource commitment. This limitation may initially be bridged by collaboration with research groups already familiar with the operation of the chosen device in simulators.

Insofar as several key issues are yet to be answered, I am at this time withholding recommendation as to the more appropriate system. This recommendation will be forthcoming by 1979 year-end after further discussion and coordination with all appropriate parties.

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FINAL REPORT

REDESIGN OF A LASER DOPPLER VELOCIMETER SYSTEM FOR UNSTEADY, SEPARATED FLOW STUDIES

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REDESIGN OF A LASER DOPPLER VELOCIMETER SYSTEM FOR UNSTEADY, SEPARATED FLOW STUDIES

by

K. Koenig

ABSTRACT

As part of a detailed investigation of the flow field about wings undergoing large amplitude, unsteady motions, a two-component laser Doppler velocimeter (LDV) has been assembled at the Frank J. Seiler Research Lab. Operational difficulties, however, have necessitated a redesign of the system configuration and optical components. This report outlines the system, its difficulties and the proposed reconfiguration. Also included are detailed discussions on pertinent optical considerations, especially concerning changes in polarization upon reflection and refraction and characteristics of prisms. The final design for the LDV system features a stacked arrangement in which the laser and optics are horizontal with the optics above the laser. The four beams are turned through 90^{o} and brought, parallel, down to the final focusing lens which forms the desired probe volume in the wind tunnel test section. This design should be nearly optimal in terms of ease of operation, measurement accuracy, ease of construction and structural rigidity.

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I would like to thank the Air Force Systems Command, Air Force Office of Scientific Research and the Southeastern Center for Electrical Engineering Education for the opportunity to spend a most interesting summer at the U.S. Air Force Academy working with the people at the Frank J. Seiler Research Lab. I also greatly appreciate the work Dr. Richard Miller has done in organizing and handling the personal aspects of this summer research program.

There are many people at the Academy with whom I have worked and who deserve a note of thanks. I greatly appreciate the support and freedom provided by Col M. D. Bacon and Lt Col J. S. Ford during my stay. Ms. Donna Weiss, Mr. Carl Geddes and Lt Clint Harper are also to be thanked for their many efforts during this work. Finally, I would like to thank Capts Mike Francis and John Keesee and Major John Retelle for the cooperation, patience, guidance and hospitality they showed me.

I. INTRODUCTION:

Motion of a wing or airfoil section in an unsteady manner can produce transient normal forces of considerable magnitude. The possibility also exists for a sudden loss in normal force, a situation known as dynamic stall, during large amplitude nonsteady motions.[1] If one were able to control these phenomena, they might be used to greatly enhance the performance of a wide variety of flight vehicles. Controlling these phenomena, however, requires a greater understanding of the basic fluid mechanics involved than is currently available. To add to our understanding, the Frank J. Seiler Research Laboratory (FJSRL) has devised a wind tunnel experiment to study in detail subsonic flow past a two-dimensional wing which can pitch and accelerate in various programmed ways.[2] This experiment should yield a substantial quantity of information on nonsteady aerodynamics which, up to now, has been needed but quite unavailable.

A primary goal of the experiment is to map the velocity field around the wing during its motion. The flow will generally be highly turbulent, of unknown mean direction and quite often reversed. In addition, the wing itself will be moving, making the region available for study by probes such as hot wires very limited. Because of these difficulties, the Lab has chosen a laser Doppler velocimeter (LDV) as the measurement tool. This LDV, based on a 4 watt argon ion laser, is a two-color, frequency-shifted system operating in a single particle, dual beam, back scatter mode. The entire system is mounted upon a traverse providing computer-controlled, two degree-of-freedom motion of the probe volume in a horizontal plane. With these features, this LDV system is capable of simultaneously measuring instantaneous values of two horizontal velocity components at a point in virtually any flow field which might be encountered. Coupling this system to a computer-controlled data acquisition system, which has been done, has resulted in an extremely powerful tool for mapping the velocity fields of interest.

Although laser Doppler velocimetry has many capabilities unmatched by any other measurement technique, it still has some disadvantages to which the system owned by the Lab is not entirely immune. This LDV system, as most, is of rather large physical dimensions, especially in comparison to the probe volume, yet it must be aligned and traversed with a very high degree of accuracy. The need for precise alignment and fine adjustments for optimizing the optics requires that all components be readily accessible and easily adjusted in an adequate number of degrees of freedom. In addition, very few wind tunnels have been constructed with the use of an LDV in mind and the tunnel to be used here is no exception. This sometimes leads to considerable difficulty in mounting the system and traverse mechanism and positioning high quality optical surfaces. In view of these difficulties and requirements, it is quite important that the layout of the laser, optics, supports and traverse be very carefully designed so that the benefits of the LDV may be realized.

At the beginning of the summer the Seiler LDV was installed on the Air Force Academy subsonic wind tunnel in the configuration shown in Figure 1. We intended to first fine tune the optical system in preparation for making measurments while the wing and related mechanisms were being finished and then to make at least preliminary measurements to wring out the entire experimental apparatus and to explore the flow. After much effort in attempting to accurately align the optical system to yield two coincident focal volumes it became evident that the optics/

traverse layout was not adequate to allow proper adjustments and that a new configuration was needed. The design of this new configuration thus became the objective of the remainder of the summer's work and is the subject of this report.

II. OBJECTIVES:

The objective of the work to be discussed here was to redesign the laser Doppler velocimeter layout according to the following design principles:

(1) Ease of operation - There should be easy access to all optical components and the layout should be compact. Sufficient adjustments are to be provided so that the beams may be precisely controlled in both direction and polarity. Possibilities for interference between hardware components or hardware and beams should be eliminated. Improve the alignment procedures.

(2) Minimization of reconfiguration effort and expense - Retain as much of the existing structural members as possible. Minimize the number of additional optical components which are required.

(3) System accuracy - Beam path lengths should be kept reasonable. The structure must be as rigid as possible. Eliminate spurious reflections and minimize laser beam power losses at optical interfaces. Maintain linearly polarized beams.

(4) Compatibility with experiment - Maintain the proper beam orientation. Maximize the area which can be covered by the probe volume.

III. THE LASER DOPPLER VELOCIMETER SYSTEM AND CONSTRAINTS:

The Seiler laser Doppler system is composed of a laser with power supply, the optical train, signal processors and a mounting and traverse system (Fig. 1). The laser is a Lexel Model 95, 4 watt argon ion laser which is operated in the multiline mode. The green 514.5 nm and blue 488.0 nm lines contain most of the power and are the lines used in this experiment. Most of the optical components are TSI (Thermo-Systems, Inc.) series 900 units. They form a compact, protected package (Fig. 2) of high quality optical pieces specifically designed for the mode of operation desired, which in this case is a two-color, frequency-shifted, back scatter, single particle, dual beam mode. Several non-TSI mirrors and mounts are also used. TSI Model 1990 counters are used to process the signals from the LDV's photomultipliers. The unique traversing and support system is composed of two Aerotech, Inc. Model ATS-412 CX Linear Translation Tables controlled by two Aerotech Model PI 4020 Parallel Load DC Drive Positioners which horizontally translate tables made of Hexel Blue Seal Sandwich Honeycomb to which the optics and laser are attached. Four turnbuckles provide vertical support and motion. The goal of the system redesign is to configure this instrumentation and hardware in such a way so as to take full advantage of each component's capabilities and at the same time optimize the ergometric characteristics of the system.

The probe volume, which is ellipsoidal in shape with its major axis vertical, is formed by the intersection of two blue and two green beams as shown in Figure 3. The blue pair measure streamwise velocities and the blue fringes move opposite to U_∞. Transverse velocities (normal to the wing) are measured by the green beams; the direction of fringe motion is not critical since the mean transverse velocity is close to zero. The desired beam polarizations are also indicated in the figure and will be discussed later. Any reconfiguration of the optics must yield the beam orientations and polarizations as described here and these consequently serve as constraints on the design.

Placement of the probe volume is another design constraint. The location of the wing and its travel define a region of space in which the probe volume is required to lie. This requirement, coupled with the wind tunnel structure and layout, limit the optical configurations which are possible, especially if the optical path length is to be kept reasonable. An excessive path length introduces considerable alignment difficulties as well as various sources of errors and inaccuracies. An optimal design attempts to avoid these problems, consequently the optics and laser must be kept as close to the desired probe locations as possible.

IV. ORIGINAL LDV/TRAVERSE SYSTEM:

The original LDV/Traverse system layout (Fig. 1) was a compact system with a minimum beam path length, two very desirable traits in principle. There were, however, serious problems which we encountered in practice and which made the system extremely difficult to use. In addition, we uncovered problems which would have made the formation of two coincident probe volumes aligned with the longitudinal and transverse flow directions nearly impossible to achieve. For these reasons the system redesign was carried out.

One major difficulty associated with the layout was the physical inaccessibility of the optics train and mirrors. This made alignment and adjustment of the optics quite difficult and also led to accidental scratches on the mirror surfaces. Another problem involved the mirror hold down devices. These were such that the mirrors were essentially impossible to translate or coarsely rotate with the optics train in the operating, i.e., vertical, position. The optics train and laser had to be removed from the traverse and laid horizontally when anything more than very minor adjustments were necessary.

Besides these operating difficulties, there were several problems which would have adversely affected the LDV's performance. The laser was mounted in an off-design orientation which might have caused problems over a prolonged period of time. The beam spacing at the individual mirrors was so close that the two mirrors had to physically overlap if the beams were to be aligned and yet not hit the mirrors on their edges. Consequently the mirrors had to be separated which then caused at least one beam to be on the edge of its mirror, a highly undesirable situation in terms of the mirror's performance. Also, the alignment technique for the blue beam using the factory supplied alignment blocks was not capable of aligning the blue beam in general. Finally, after exhaustive but futile attempts to obtain two coincident probe volumes (with the optics removed from the traverse and laid out horizontally), we found that the blue Bragg cell was not working properly and that two coincident volumes were simply not possible.

The frustrations resulting from these difficulties eventually led us to investing considerable time and money redesigning the LDV/Traverse system as described here.

V. OPTICAL CONSIDERATIONS:

During the design of a LDV optical layout there are a number of optical phenomena and requirements which must be considered. Beams must be guided through sometimes circuitous routes from the laser to the desired probe volume location. Polarization of the beams must be controlled so that the various optical devices (for example, beam splitters) operate in their most efficient manner and that the beams are correctly polarized at the probe volume. With two color systems the two beams must be adequately spaced to allow independent control and yet kept close enough to permit the use of a single device when possible (such as using one mirror to turn both beams 90°). The quality of each optical device is of concern in regards to such things as maximizing the transmission or reflectance (depending on the device) or minimizing the dispersion of the individual beams after they have been split into the desired colors. The effects of propagation of the beams through various media on the calibration constant and probe volume location must be considered. Alignment procedures should be optimized. Other concerns may arise during an LDV design but the items outlined here were the primary concerns encountered during the current reconfiguration of the Seiler LDV. Some of these topics are discussed in various texts on optics or laser Doppler velocimetry[3-8] while others require some additional derivations or calculations. Some of the more important considerations applicable to the present work will be discussed below and the appropriate calculational details or derivations included in the Appendices.

A. Some vector relations

Guiding a light beam from the laser to the probe volume requires knowing where it goes after it strikes a mirror. A useful equation may be derived which relates unit vectors of the incident beam, the normal to the mirror and the reflected beam, $\hat{e}_I$, $\hat{e}_N$ and $\hat{e}_R$ respectively. This relation,

$$\hat{e}_R = \hat{e}_I - 2(\hat{e}_N \cdot \hat{e}_I)\hat{e}_N \tag{1}$$

emphasizes the fact that translation of a mirror will cause the reflected beam to move only parallel to itself. This fact is quite useful in final placement of a beam through the optical train.

Another useful expression may be found which relates the direction cosines of a vector to the projection of that vector in one of the Cartesian coordinate planes. For example, if $\hat{e} = \cos\alpha\,\hat{i} + \cos\beta\,\hat{j} + \cos\gamma\,\hat{k}$ and the vector $\hat{e}$ is projected onto the xy plane, then

$$\cos\alpha' = \frac{\cos\alpha}{\sin\gamma} \quad \text{and} \quad \cos\beta' = \frac{\cos\beta}{\sin\gamma} \tag{2}$$

where α' and β' are the angles the projection makes with the x and y axes respectively. These expressions are convenient when laying out an optical system in which the beams travel in three dimensions.

The proofs for equations (1) and (2) may be found in the Appendices. These relations were used during preliminary design of the new layout.

B. Polarization

In terms of the Seiler LDV there are several requirements on the polarization of the light beams. All four beams (two blue and two green) which converge at the probe volume must be linearly polarized as shown in Figure 3. Each pair (the blue or the green) must be polarized in the same direction and, optimally, that direction should be perpendicular to the plane defined by a given pair. If a given pair are cross polarized there will be no interference fringes formed at the probe volume. (See References 3 or 4 for proof.) These requirements are necessary in order to maximize the Doppler signal produced as a particle traverses the probe volume and are common to any LDV. An additional requirement is imposed by the beam splitters used by TSI. In order to insure a 50/50 split with both output beams of the same linear polarization, the input beam should be linearly polarized perpendicular to the plane defined by the two output beams as shown in Figure 4a.

References 6, 7 and 8 describe in detail the changes in polarization which occur when a beam encounters an interface and is reflected and transmitted. The requirements of the Seiler LDV are such that we desire, at all times, linearly polarized light; the light emitted by the laser is linearly polarized and at no time is any other polarization required. We can quite simply summarize the detailed theory found in References 6, 7 and 8 by noting those results which are appropriate to our situation as follows.

Some definitions are required first, however. The plane defined by the normal to the interface and the incident beam is called the plane of incidence (Fig. 4b). The angle of incidence is the angle θ_i between the normal and the incident beam. The azimuth of polarization, α, of a linearly polarized beam is the angle between the plane of incidence and the electric vector of the beam; α is positive clockwise about the direction of propagation and $-\pi/2 \leq \alpha \leq \pi/2$. If $\alpha = 0$ rad or an even multiple of $\pi/2$, this is referred to as TM (transverse magnetic) or p-polarization; $\alpha =$ an odd multiple of $\pi/2$ is termed TE (transverse electric) or s-polarization. External reflection involves a beam in a medium with index of refraction n_1 striking a medium with index $n_2 > n_1$ (such as a beam in air striking glass or metal). Internal reflection is the opposite situation. At an interface between two dielectrics (such as air and glass) both a reflected and transmitted beam exist except for the case of total internal reflection. In total internal reflection θ_i is such that there is no real solution to Snell's law, $\frac{\sin \theta_i}{\sin \theta_t} = \frac{n_2}{n_1}$ for θ_t and therefore all the light is reflected. We call the value of θ_i for which this first occurs, θ_c. At θ_i equal to Brewster's angle θ_B (or the polarizing angle) no component of the electric vector parallel to the plane of incidence is reflected at dielectric/dielectric interfaces.

We can decompose the electric vector of each beam (incident, reflected and transmitted) into a component parallel to, denoted by the subscript $\parallel$, and a component perpendicular to, subscript $\perp$, the plane of incidence. We also let A be the complex amplitude of the incident electric vector and R and T the reflected and transmitted vectors, respectively. Application of the appropriate boundary conditions to Maxwell's equations then eventually leads us to the following results (taken from Sections 1.5.2 through 1.5.4 of Born and Wolf[8]).

For an interface between two dielectrics and excluding total internal reflection, we have the Fresnel formulae,

$$R_\parallel = \frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)} A_\parallel \qquad R_\perp = \frac{-\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)} A_\perp \tag{3}$$

$$T_\parallel = \frac{2 \sin \theta_t \cos \theta_i}{\sin(\theta_i + \theta_t)\cos(\theta_i - \theta_t)} A_\parallel \qquad T_\perp = \frac{2 \sin \theta_t \cos \theta_i}{\sin(\theta_i + \theta_t)} A_\perp . \tag{4}$$

Because we have excluded total internal reflection, all quantities in these equations are real. Consequently the phase differences between the incident components and the reflected or transmitted components of the electric vector are either 0 or π, depending on the signs. Therefore, for <u>all</u> cases in which a linearly polarized light beam strikes the interface between two dielectrics and total internal reflection does not occur, the reflected and transmitted beams <u>will</u> <u>remain</u> linearly polarized. However, the azimuth of polarization will not, in general, be the same. The azimuths can be found simply from equations (3) and (4) and the relations

$$\tan \alpha_i = \frac{A_\perp}{A_\parallel}, \quad \tan \alpha_r = \frac{R_\perp}{R_\parallel}, \; \tan \alpha_t = \frac{T_\perp}{T_\parallel} . \tag{5}$$

These give

$$\tan \alpha_r = \frac{-\cos(\theta_i - \theta_t)}{\cos(\theta_i + \theta_t)} \tan \alpha_i \tag{6}$$

$$\tan \alpha_t = \cos(\theta_i - \theta_t)\tan \alpha_i . \tag{7}$$

Since $0 \leq \theta_i \leq \pi/2$ and $0 < \theta_t < \pi/2$, we also find that

$$|\tan \alpha_r| \geq |\tan \alpha_i| \quad \text{and} \quad |\tan \alpha_t| \leq |\tan \alpha_i| . \tag{8}$$

For total internal reflection the Fresnel formulae (3) and (4) show that $|R_\parallel| = |A_\parallel|$, $|R_\perp| = |A_\perp|$ and $|T_\parallel| = |T_\perp| \equiv 0$. However, equations (3) and (4) are now complex and the phase change of each component, denoted by $\delta_\parallel$ and $\delta_\perp$, is now not a multiple of π, and in general $\delta_\parallel \neq \delta_\perp$. The phase changes are found to be

$$\tan \frac{\delta_\parallel}{2} = \frac{\sqrt{\sin^2\theta_i - n^2}}{n^2 \cos \theta_i} \tag{9}$$

and

$$\tan\frac{\delta_\perp}{2} = \frac{-\sqrt{\sin^2\theta_i - n^2}}{\cos\theta_i} . \tag{10}$$

More important is the relative phase difference $\delta = \delta_\perp - \delta_\parallel$ which is given by

$$\tan\frac{\delta}{2} = \frac{\cos\theta_i\sqrt{\sin^2\theta_i - n^2}}{\sin^2\theta_i} . \tag{11}$$

Since δ is not a multiple of π, the reflected wave will be elliptically polarized unless $A_\parallel$ or $A_\perp$ is zero. Consequently it is important to have TM or TE incident beams in total internal reflection in order to insure that the light is always linearly polarized.

The situation for reflection at a dielectric/metal interface is more complex. The most important result can be simply put, however. In general a linearly polarized beam becomes elliptically polarized upon reflection from a metal surface unless the incident beam is of either TM or TE polarization, i.e., $\alpha_i = 0$ or $\pi/2$. Just as with total internal reflection, it is necessary to have the proper incident polarization in order to keep the light linearly polarized everywhere.

C. Prism Characteristics

The Seiler LDV requires splitting the multiline argon ion laser beam into its component colors and sending two, the green 514.5 nm and blue 488.0 nm, down the TSI optical train. In order to optimize the layout, consideration was given to using a prism to provide additional spacing between the green and blue beams beyond the spacing created by the TSI color splitter (or dispersion prism) unit. This additional spacing would help in situating the individual mirrors which control the final orientation of the two beams into the TSI optical train. During consideration of the prism, several prism characteristics were investigated. Although the final design does not include an additional prism, the color splitter does use prisms and a brief discussion of some of the prism characteristics may be helpful.

An equilateral dispersing prism is shown in Figure 5a and a right angle prism in Figure 5b. By repeated use of Snell's law, $\frac{\sin \theta_i}{\sin \theta_t} = \frac{n_2}{n_1}$ and some elementary geometry, the total angular deflection $\Delta\theta$ caused by each prism can be found in terms of the initial angle of incidence θ_1 and the prism and surrounding media indices of refraction. For the equilateral prism as shown in Figure 5a,

$$\Delta\theta = \sin^{-1}\left\{\frac{n_2}{n_3}\sin\left[60^o - \sin^{-1}\left(\frac{n_1}{n_2}\sin\theta_1\right)\right]\right\} + \theta_1 - 60^o \quad . \tag{12}$$

For the right angle prism as shown in Figure 5b

$$\Delta\theta = 90 - 2\theta_1 \tag{13}$$

(where the surrounding medium is all the same). Other orientations are possible but these are the most useful configurations. Equation (12) is plotted in Figure 5c for a BK-7 crown glass prism and a green 514.5 nm incident beam ($n = 1.52065$) surrounded by air. Notice the limited range for $\Delta\theta$.

A prism is capable of splitting the multiline argon ion beam into its component colors because the index of refraction of glass is, in general, a function of wavelength, i.e., $n = n(\gamma)$. Since the component colors are not absolutely pure, however, the use of another prism to increase the beam spacing might cause an additional spread or dispersion in the beam passing through the prism. To check the dispersion that might occur, the following calculation using the green, 514.5 nm,beam of the argon laser and BK-7 crown glass prism was made.

Each component of the laser beam has a bandwidth,[9] Δf, of approximately 5 GHz; thus, $f_{green} = 5.83 \times 10^{14} \pm 2.5 \times 10^{6}$ Hz and 514.498 nm < λ_{green} < 514.502 nm (using $f\lambda = c = 3 \times 10^{8}$ m/sec). At 546.1 nm the index of refraction of BK-7 glass[5] is 1.51872, at 486.1 nm, n = 1.52238. Linearly interpolating shows that the change in n, Δn, over the wavelength range of the green beam is only 5.3×10^{-7} which is four orders of magnitude less than Δn between the primary blue, 488.0 nm, and primary green, 514.5 nm, beams. The angular spread in the green beam caused by this Δn is only 1.4×10^{-4} deg or 2.4×10^{-3} milliradians, a quite negligible amount compared to the 0.6 milliradian divergence inherent in the beam when it initially leaves the laser.

When a multiline laser beam passes through a prism, a series or fan of light beams, all lying in the same plane, is produced as the output. If the incident beam is linearly polarized with the electric vector parallel to the plane of the fan, then the output beams will also be linearly polarized parallel to this plane. This situation is shown in Figure 4c. The TSI Model 905 Color Splitter is composed of two dispersion prisms and a dielectric-coated mirror. The polarization of the color splitter output beams will also be in the plane of the fan if the input beam is polarized in that way.

The cross-section of the dispersion prism output beams will be round when the prism is oriented so that $\Delta\theta$ (see Figure 5c) is a minimum. For other angles of incidence, θ_1, the beam cross-sections are elliptical. The minimum in $\Delta\theta$ can easily be found by rotating the dispersion prism about an axis parallel to the input beam and observing when the output beams reverse their direction of travel.

VI. THE RECONFIGURED LDV/TRAVERSE SYSTEM:

Considerable effort has been spent in reconfiguring the laser, optics and traverse systems and many layouts and detailed designs have been considered. An example of one of the preliminary designs is shown in Figure 6. In this design all components are on one horizontal surface. There is no interference, all components are accessible, the laser is oriented correctly and there is ample spacing between the beams at the individual color mirrors. The disadvantage of this system (and the reason why this design was rejected) is the excessive size of the layout. With the existing support structure, the components are cantilevered over long spans which presents bending and balancing problems. In addition, the surface on which the components sit is large enough that in some positions of the system a person cannot reach some components. Generally, all layouts in which the components sit on one horizontal surface suffer from at least one of these two problems and are therefore unsatisfactory.

Configurations in which the optics are oriented vertically are also generally unacceptable. In order to improve accessibility, the optics must be raised above all the supporting tables. This results in a very unwieldly system that is difficult to balance and support so that it does not suffer from vibration problems. In addition, the laser beam paths are long and cross eye level which creates a safety hazard.

A design which, although not immune from problems, seems to be the most satisfactory is one in which the optics and laser are horizontal but where the optics are stacked above the laser. Our proposed scheme is shown in a side view in Figure 7. A series of mirrors bring the two beams back the length of the laser, up to the optics train level and finally into the optics, parallel and spaced 51.7 mm apart. The spacing is very good at the two individual mirrors; the mirrors are all quite accessible and have finely adjustable traverses (from Oriel Corporation) where needed to allow complete control of the beams. All the optics which require adjustment are in fact readily accessible and at a more convenient working height. The laser is oriented in its design position. Figures 8 and 9 show top and end views of this same design. (Certain details and dimensions shown in Figures 7 through 9 will not be the same as the final design. However, the qualitative features and the design concept are correct with respect to the final LDV layout.)

Besides the improvements in the general layout of the LDV as shown in Figures 7 through 9, several improvements in the optical equipment itself have been made or planned. A TSI Model 975 Beam Steering Module has been added to compensate for the inaccuracies in the blue Bragg cell. This unit will permit the formation of two coincident probe volumes. Two contemplated changes are the addition of a Beam Expander system (TSI 988, plus another 975 Steering Module and two 913-22 Beam Spacers) which will provide up to a factor of 5 increase in Signal-to-Noise Ratio (SNR) and the installation of two TSI Model 10905 Back Scatter Conversion Kits which will further raise the SNR by improving the image focused upon the photomultiplier tubes. To complement these changes, the other optical components being purchased (the two individual mirrors, the second mirror and the final mirror which brings the beams down) will have dielectric coatings which give the mirrors 99% reflectance of S or P (TE or TM) polarized light at both 488.0 and 514.5 nanometers. These units are $\lambda/20$ Pyrex mirrors with a Broadband-Dielectric coating and are obtained from Newport Research Corporation (NRC). The net result of these optical changes should be a significant performance improvement despite the addition of two mirrors and increased beam path lengths.

There are several disadvantages to this proposed system layout however. The laser and optics are not as well balanced or supported as the original design, even though one of the motor/traverse plates has been moved outboard. There are more optical components, they require more adjustments and the beam path lengths are increased. The most serious disadvantage to the layout as proposed is the requirement that two alignments, one horizontal and one vertical, be made. The beams must first be made parallel and equally spaced about the horizontal optical axis of the optics train. The four beams (two blue and two green) must then be turned 90° and brought down to the final focusing lens. The four beams, prior to striking the lens, must be parallel to and equally spaced about the optical axis of this lens. In order to insure this vertical alignment, the arrangement shown in Figure 10 is proposed. A 4" NRC mirror, mounted on a two rotation mirror mount which is, in turn, mounted to a NRC translation stage turns the beams 90°. An alignment tool consisting of holes drilled in a mask at the desired beam locations is mounted between the mirror and final lens. Adjustment of the mirror and use of the mask will provide sufficient control to align the beams vertically. (Again some details in Figure 10 may not remain the same but the concept is correct.)

A necessary requirement for any layout is that it permits positioning of the probe volume in the desired region of space. Considerable effort has been put into the design to insure that the traversing capability of the system is used to its fullest and that the laser can access all flow regions of interest. In this experiment a 6 inch chord airfoil translates along a longitudinal 12 inch slot while it pitches about the 45% chord location. A 14 inch diameter optical window is placed in the wind tunnel ceiling so that the flow area around the airfoil which is of most interest is accessible to the laser beams. The window position in this case is centered longitudinally and 1/2 inch to the north side of the slot. The LDV translation tables provide 12 inches of travel longitudinally and transversely. The design presented here positions the optics so that with each table at the center of its travel, the optical axis of the final focusing lens passes through the center of the 14 inch optical window. The layout design then allows for the full 12 inches of travel in each direction without interference with any part of the wind tunnel structure or the LDV support system. Figure 11 shows a top view of the new LDV layout with the supporting structure, slot and access holes detailed.

The system as described in this section should be an instrument which is easy to operate, uses the various components effectively, is accurate and reliable. In addition, details of the design, many of which are not included in this report, are such that the layout is fairly flexible and can be further improved or possibly used in other experiments with a minimum of effort. This proposed configuration seems to most fully meet the requirements and guidelines imposed by the experiment and should perform quite well in measuring turbulent flow past a nonsteady airfoil.

VII. RECOMMENDATIONS:

Due to the nature of this work, the recommendations are rather simple and straightforward. The system configuration as described in Section VI is obviously recommended as the LDV layout to use for the Seiler nonsteady airfoil experiments. Many details of the design are not included in this report, however. Such things as exact mirror locations and orientations, base plate hole patterns, mounts for the dispersion prism (color splitter) and some of the mirrors, details of the alignment mask-final lens vertical member and location of the entire system relative to the wind tunnel test section have not been discussed. Many of these details are recorded on design drawings on file with Seiler Lab. Other details still must be determined or will evolve naturally as the system is assembled. In determining any of the final details, it is recommended that they be compatible with those details already prescribed and that they follow the principles set forth in Section II of this report.

The immediate follow-on to the present work should include careful cleaning of all optical components, development of a blue beam alignment procedure and construction of the system itself. Once the layout has been assembled, a careful study of its performance and characteristics should be made. This study should include a quantitative assessment of the size and shape of the probe volume as well as signal strength and signal to noise ratio. Finally, measurements should be made of known flows to check the entire system performance.

Considerable care has been taken during the design of this layout to optimize the system as whole for maximum performance while requiring minimum effort of construction and operation. Undoubtedly, though, problems will arise. Some problems can be avoided if the construction is also done carefully. For example, accurate placement of mounting holes for the optical components will simplify alignment procedures. It would also be wise to provide extra mounting holes or slots whenever possible to add some flexibility to the system and permit coarse adjustments with the optics in place rather than require disassembly and additional drilling to correct a problem. Steps such as these should eliminate much of the potential trouble which will be encountered as the system is used; other problems may require minor modifications or additional parts but hopefully these will be few. In any case, it now requires construction and use of the proposed layout before any further assessment of the design can be made.

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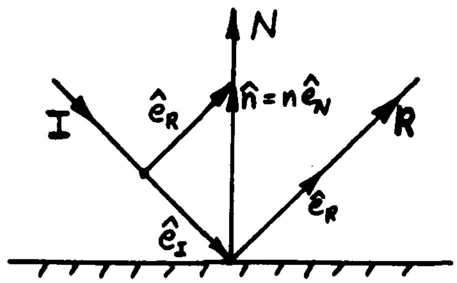
APPENDIX A

Direction of a Reflected Light Ray

Consider a light ray I incident on a surface with normal N. The unit vectors $\hat{e}_I$ and $\hat{e}_N$ are known and we wish to find $\hat{e}_R$, the unit vector for the reflected ray R.



The following facts are required:

1. $\hat{e}$ = any unit vector = $\hat{i}\cos\alpha + \hat{j}\cos\beta + \hat{k}\cos\gamma$, $0 \leq \alpha, \beta, \gamma \leq \pi$.
2. The magnitude of $\hat{e} = |\hat{e}| = \cos^2\alpha + \cos^2\beta + \cos^2\gamma = 1$.
3. $\hat{e}_1 \cdot \hat{e}_2 = \cos\alpha_1 \cos\alpha_2 + \cos\beta_1 \cos\beta_2 + \cos\gamma_1 \cos\gamma_2$.
4. The vector $\vec{c} = \vec{a} \pm \vec{b}$ lies in the plane defined by $\vec{a}$ and $\vec{b}$.

Now $\vec{n} = \hat{e}_R - \hat{e}_I = n\hat{e}_N$ where n is some magnitude. From 4 then $\hat{e}_N$, $\hat{e}_R$ and $\hat{e}_I$ all lie in the same plane. From 2 we have that $|\hat{e}_I| = |\hat{e}_R|$. We now have two unknowns n and $\hat{e}_R$ but we also have two equations, that is

$$n\hat{e}_N = \hat{e}_R - \hat{e}_I \quad \text{and} \quad |\hat{e}_R| = |\hat{e}_I| = 1.$$

Rewriting the first of these equations as $\hat{e}_R = \hat{e}_I + n\hat{e}_N$ and substituting from 1 gives

$$\hat{e}_R = (n\cos\alpha_N + \cos\alpha_I)\hat{i} + (n\cos\beta_N + \cos\beta_I)\hat{j} + (n\cos\gamma_N + \cos\gamma_I)\hat{k}.$$

Finding the magnitude of each side then gives

$$|\hat{e}_R| = 1 = (n\cos\alpha_N+\cos\alpha_I)^2 + (n\cos\beta_N+\cos\beta_I)^2 + (n\cos\gamma_N+\cos\gamma_I)^2$$

or

$$n^2(\cos^2\alpha_N+\cos^2\beta_N+\cos^2\gamma_N) + 2n(\cos\alpha_N\cos\alpha_I+\cos\beta_N\cos\beta_I+\cos\gamma_N\cos\gamma_I)$$

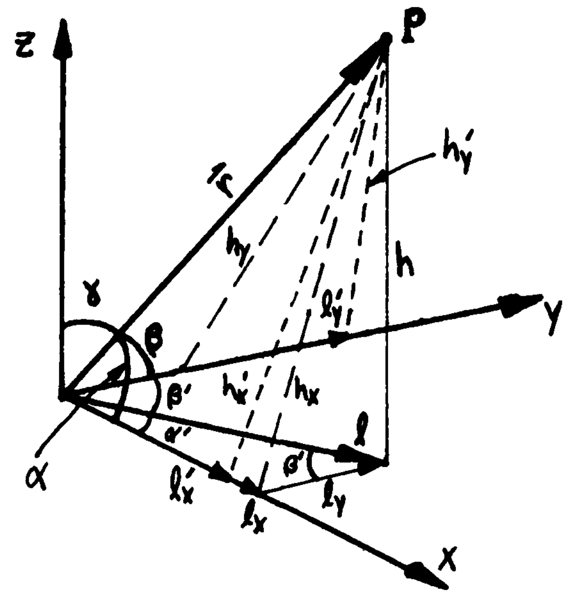
$$+(\cos^2\alpha_I+\cos^2\beta_I+\cos^2\gamma_I) = 1 \cdot$$

Using 2 and 3 then gives $n^2 + 2n\ (\hat{e}_N \cdot \hat{e}_I) + 1 = 1$ which reduces to $n = -2\ (\hat{e}_N \cdot \hat{e}_I)$. Substituting this back into $\hat{e}_R = \hat{e}_I + n\hat{e}_N$ finally gives $\hat{e}_R = \hat{e}_I - 2(\hat{e}_N \cdot \hat{e}_I)$ which is the desired result.

APPENDIX B

The Projection of a Vector onto a Plane

Consider the vector $\vec{r} = r\hat{e} = r(\hat{i} \cos \alpha + \hat{j} \cos \beta + \hat{k} \cos \alpha)$ as shown below.



The projection of $\vec{r}$ onto the x-y plane is ℓ with components ℓ_x and ℓ_y and the height of the vertical is h. Also consider the projection of $\vec{r}$ onto the x and y axes, ℓ_x' and ℓ_y' respectively. We will first show that $\ell_x' = \ell_x$ and $\ell_y' = \ell_y$, then finish the proof of equations (2).

By definition, h_x' is perpendicular to the x axis. Now ℓ_y and h define a plane which also contains h_x. By definition, $\ell_y \perp$ x axis and $h \perp$ x axis. Therefore, every line in the plane defined by ℓ_y and h is also $\perp$ x axis and thus $h_x \perp$ x axis. Now h_x and h_x' are both $\perp$ x axis and both pass through point P. Consequently, h_x and h_x' are the same line and ℓ_x and ℓ_x' are the same line and $\ell_x = \ell_x'$. An identical argument will show that $\ell_y = \ell_y'$.

Now $\ell_x' = r \cos \alpha$, $\ell_x = \ell \cos \alpha' = r \sin \gamma \cos \alpha'$, and since $\ell_x' = \ell_x$, we then have $\cos \alpha' = \frac{\cos \alpha}{\cos \gamma}$. Similarly we find $\cos \beta' = \frac{\cos \beta}{\cos \gamma}$.

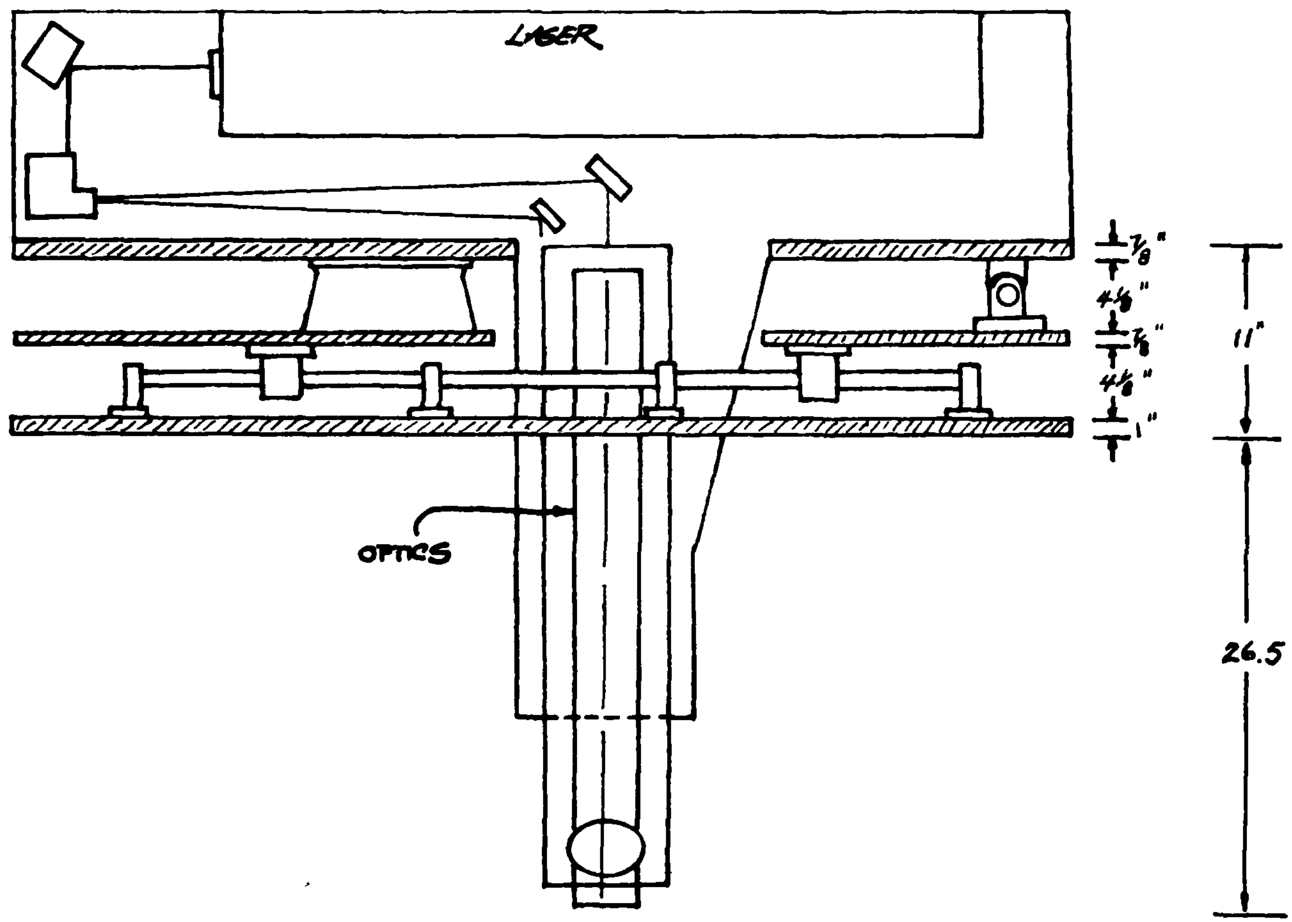


FIGURE 1. ORIGINAL LDV/TRAVERSE LAYOUT

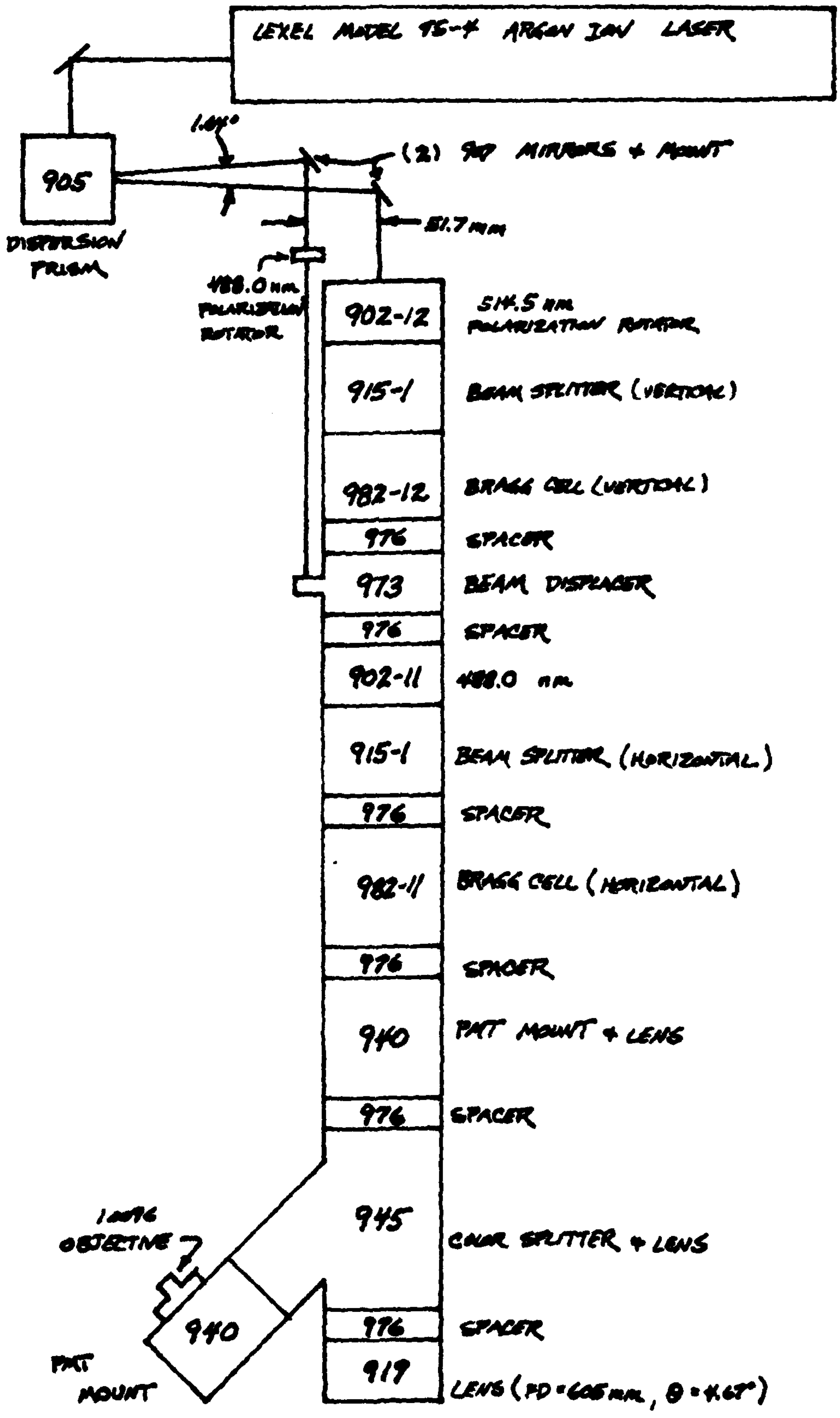


FIGURE 2 OPTICAL TRAIN

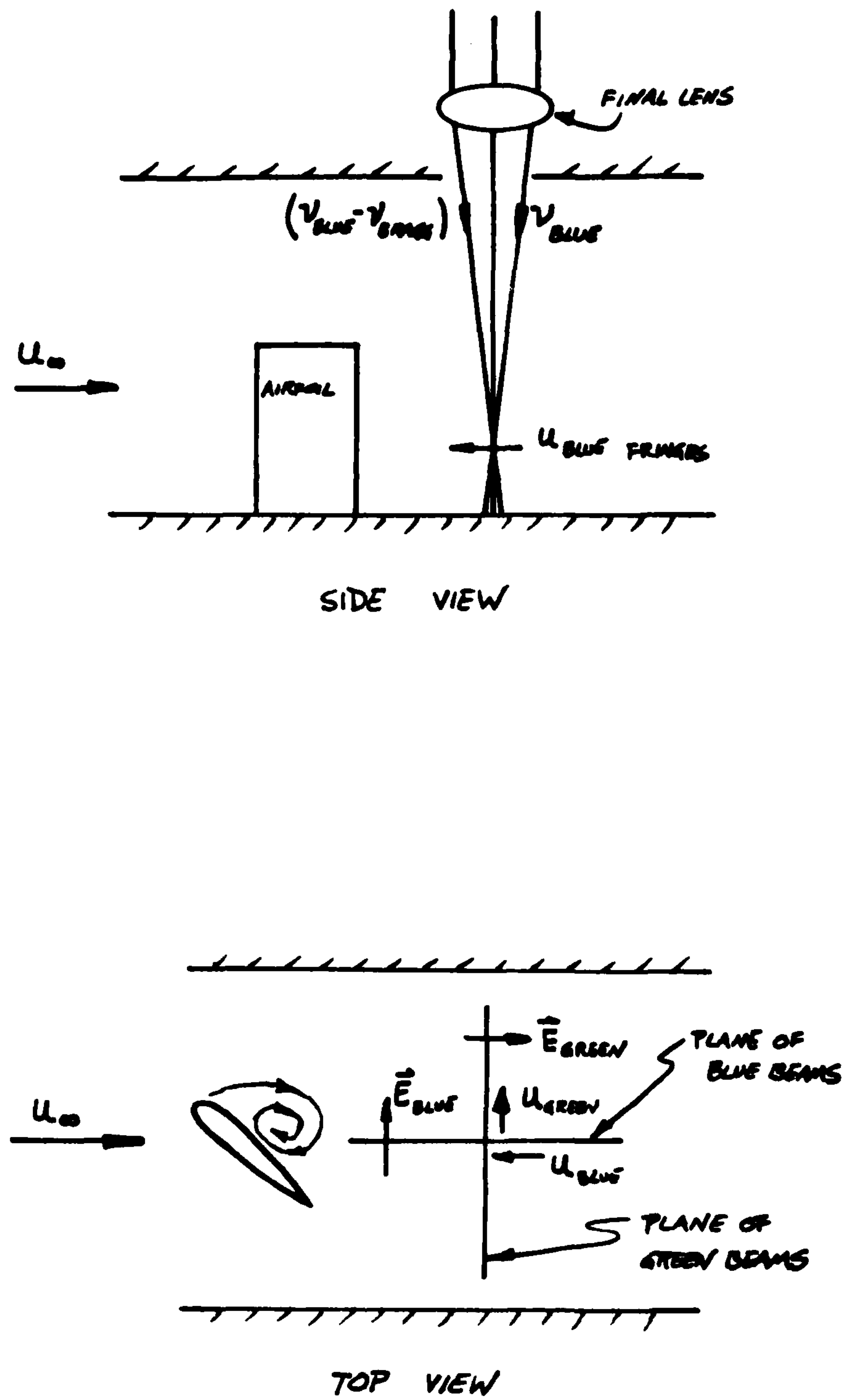
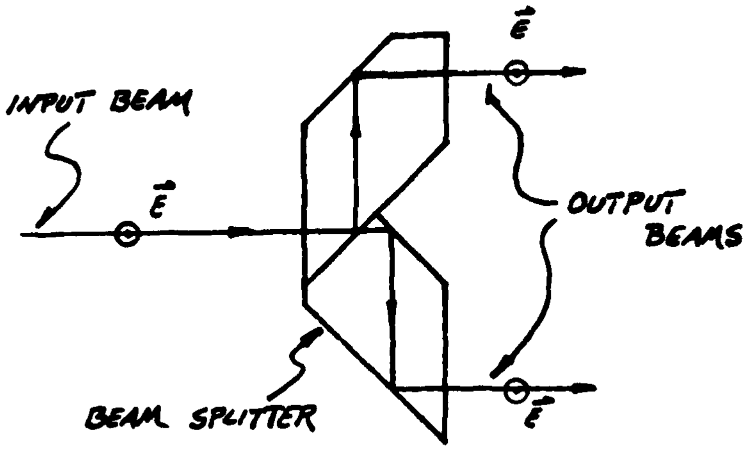
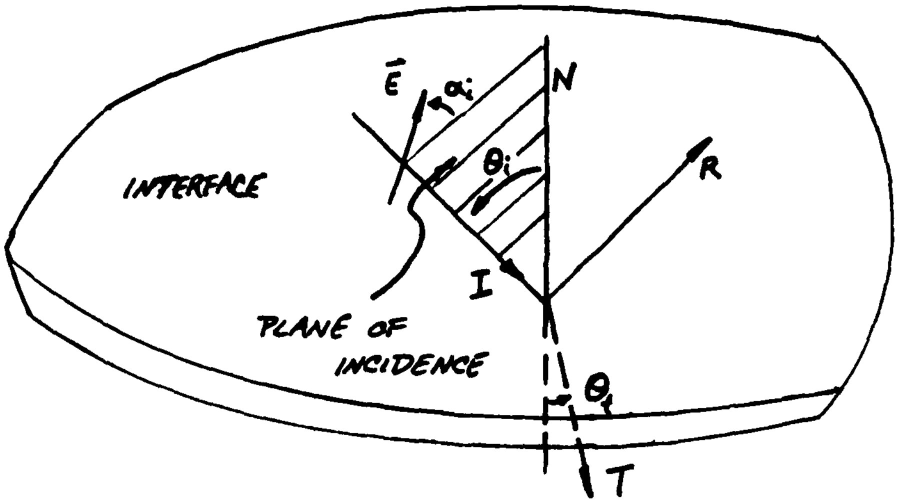


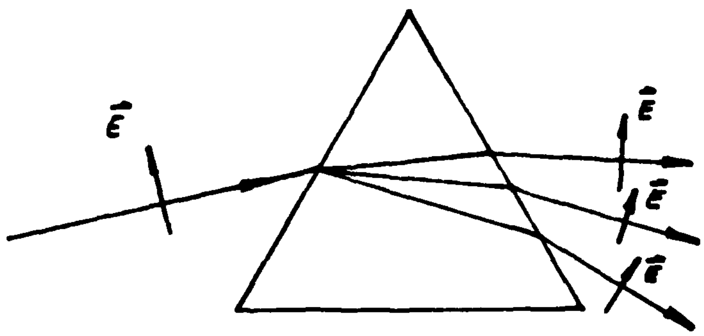
FIGURE 3. BEAM CONFIGURATION



a. BEAM SPLITTER

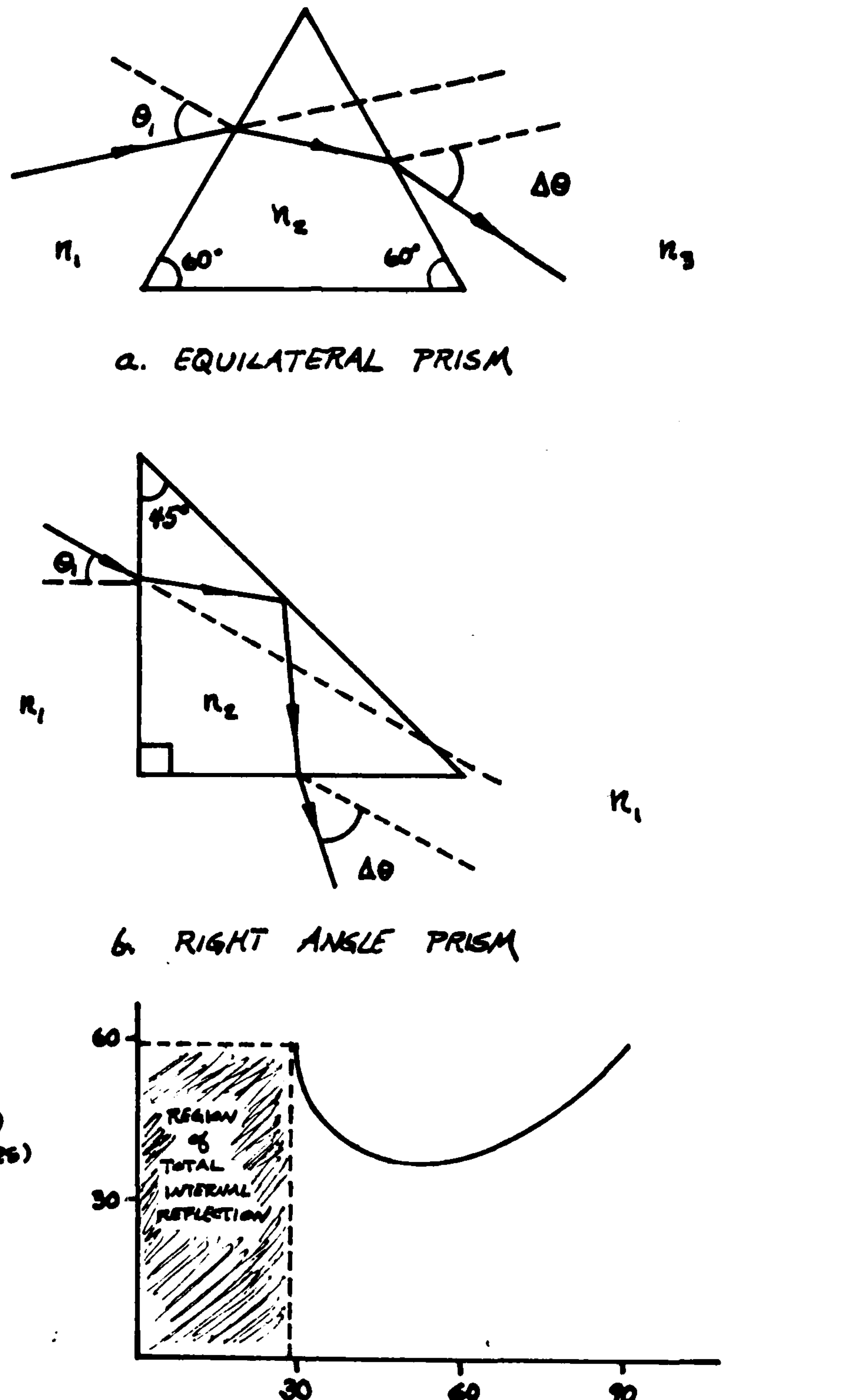


b. BEHAVIOR AT AN INTERFACE



C. DISPERSION PRISM

FIGURE 4. POLARIZATION



a. EQUILATERAL PRISM

b. RIGHT ANGLE PRISM

C. BEAM DEFLECTION, EQUILATERAL PRISM

FIGURE 5. PRISM CHARACTERISTICS

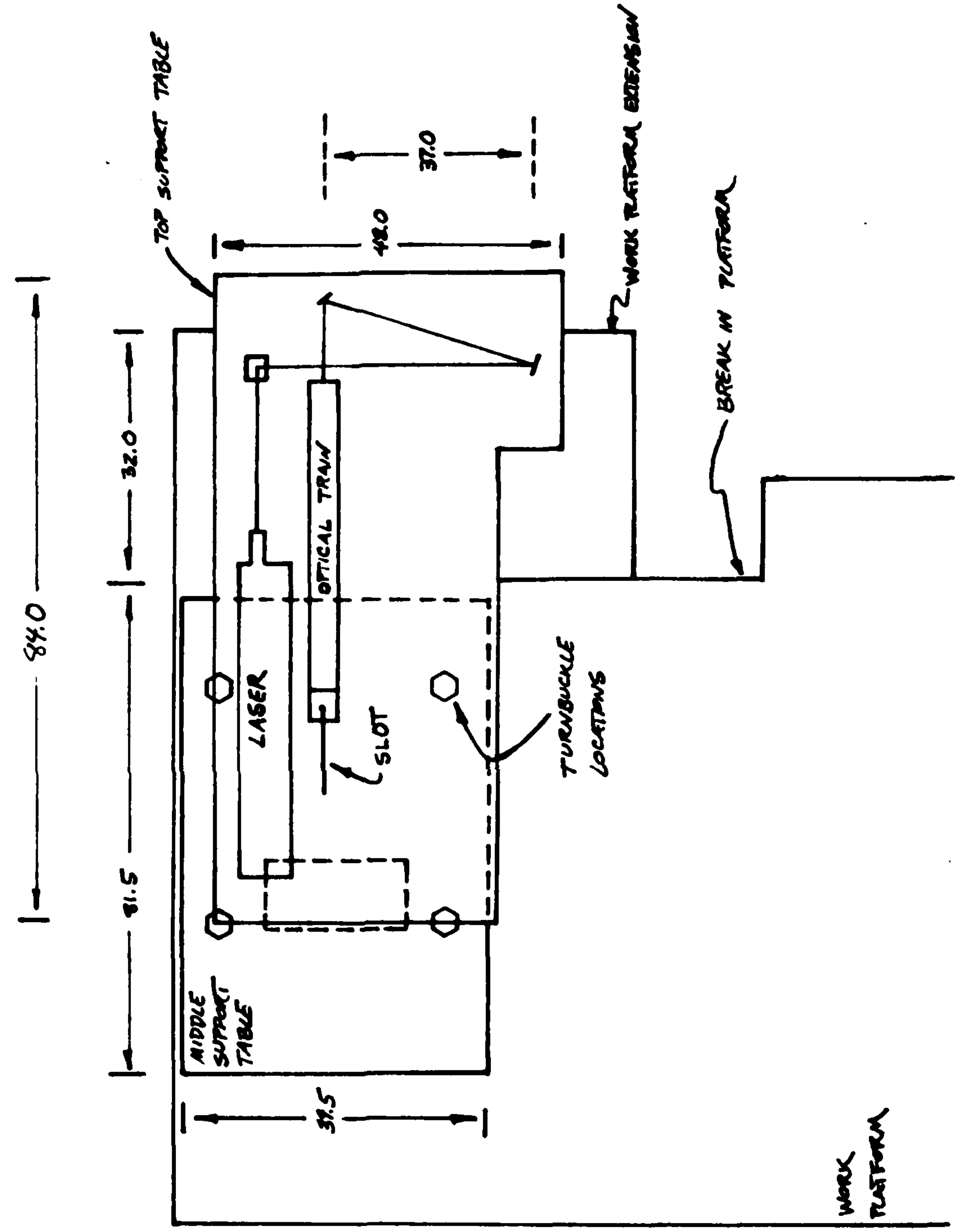


FIGURE 6. POSSIBLE HORIZONTAL LAYOUT

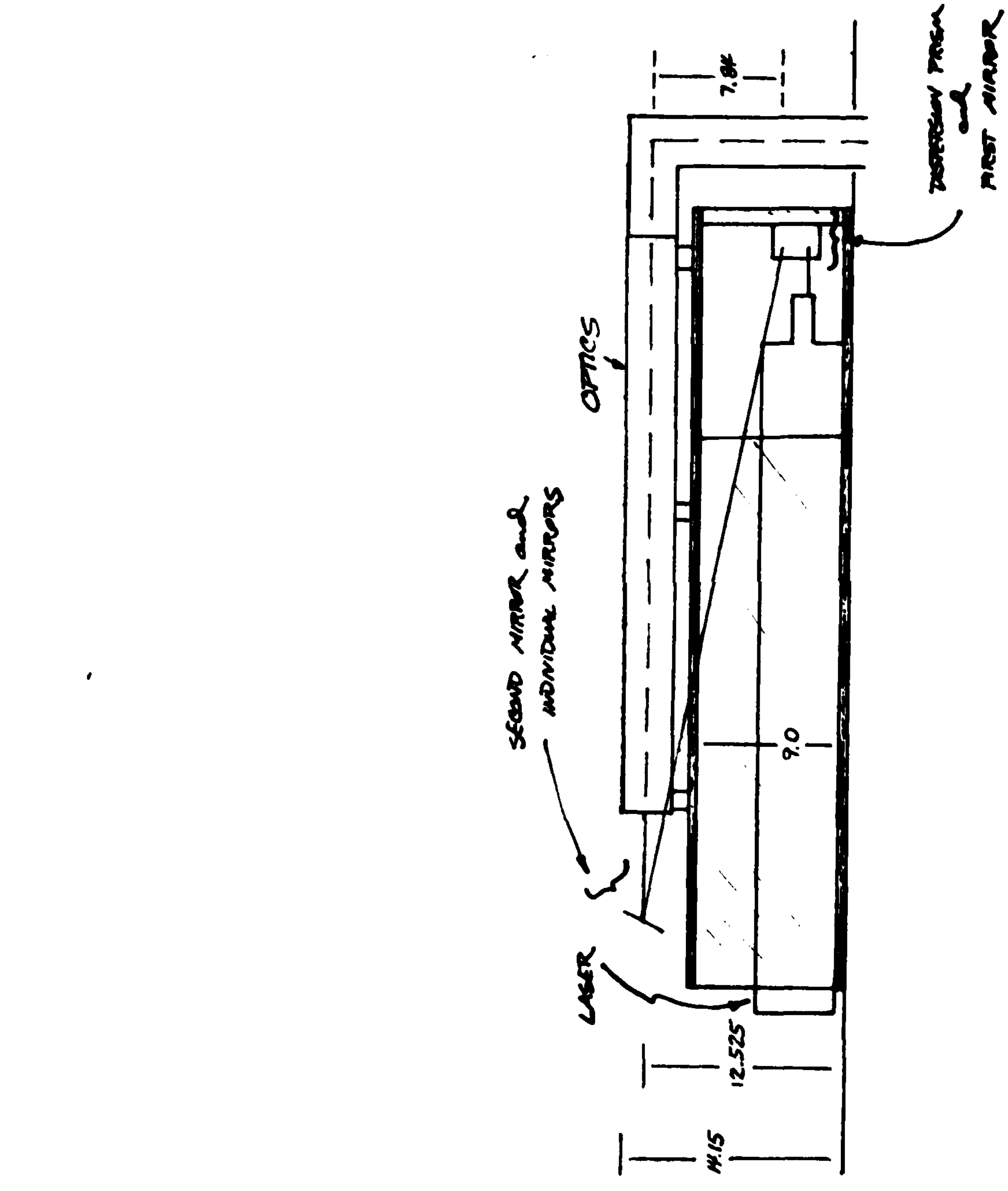


FIGURE 7. FINAL PROPOSED LAYOUT, SIDE VIEW

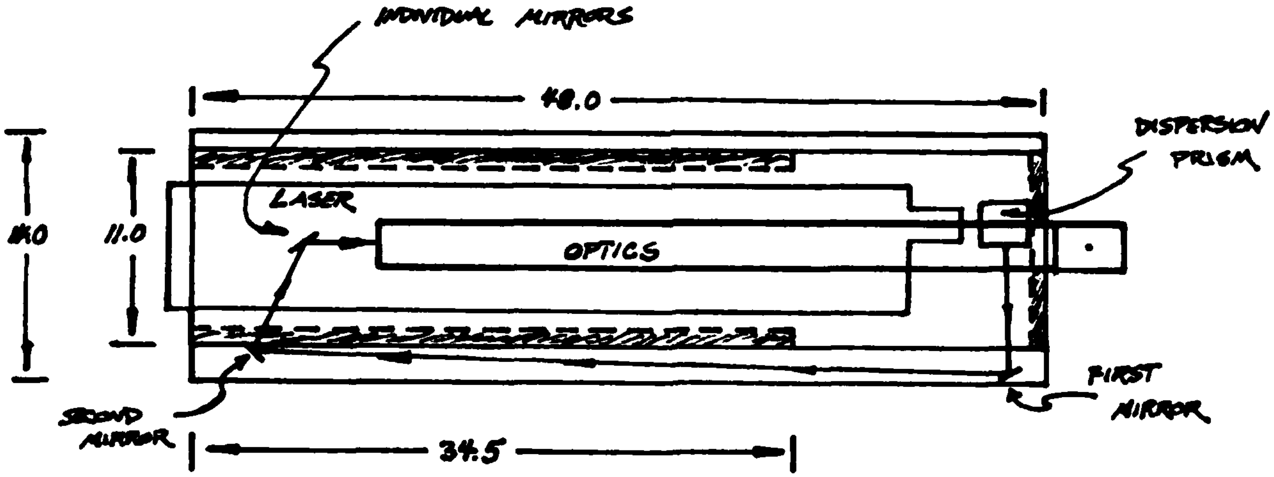


FIGURE 8. FINAL PROPOSED LAYOUT, TOP VIEW

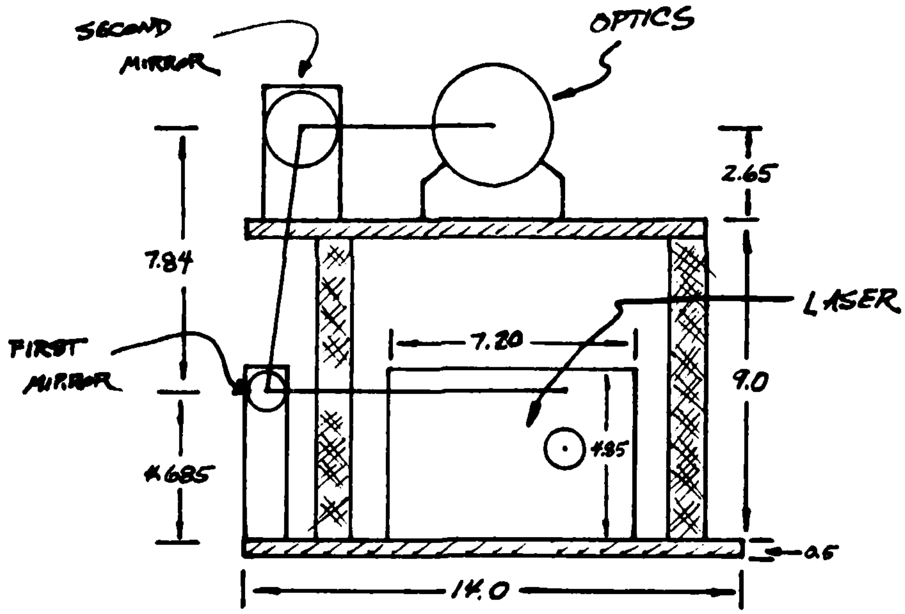


FIGURE 9. FINAL PROPOSED LAYOUT, END VIEW

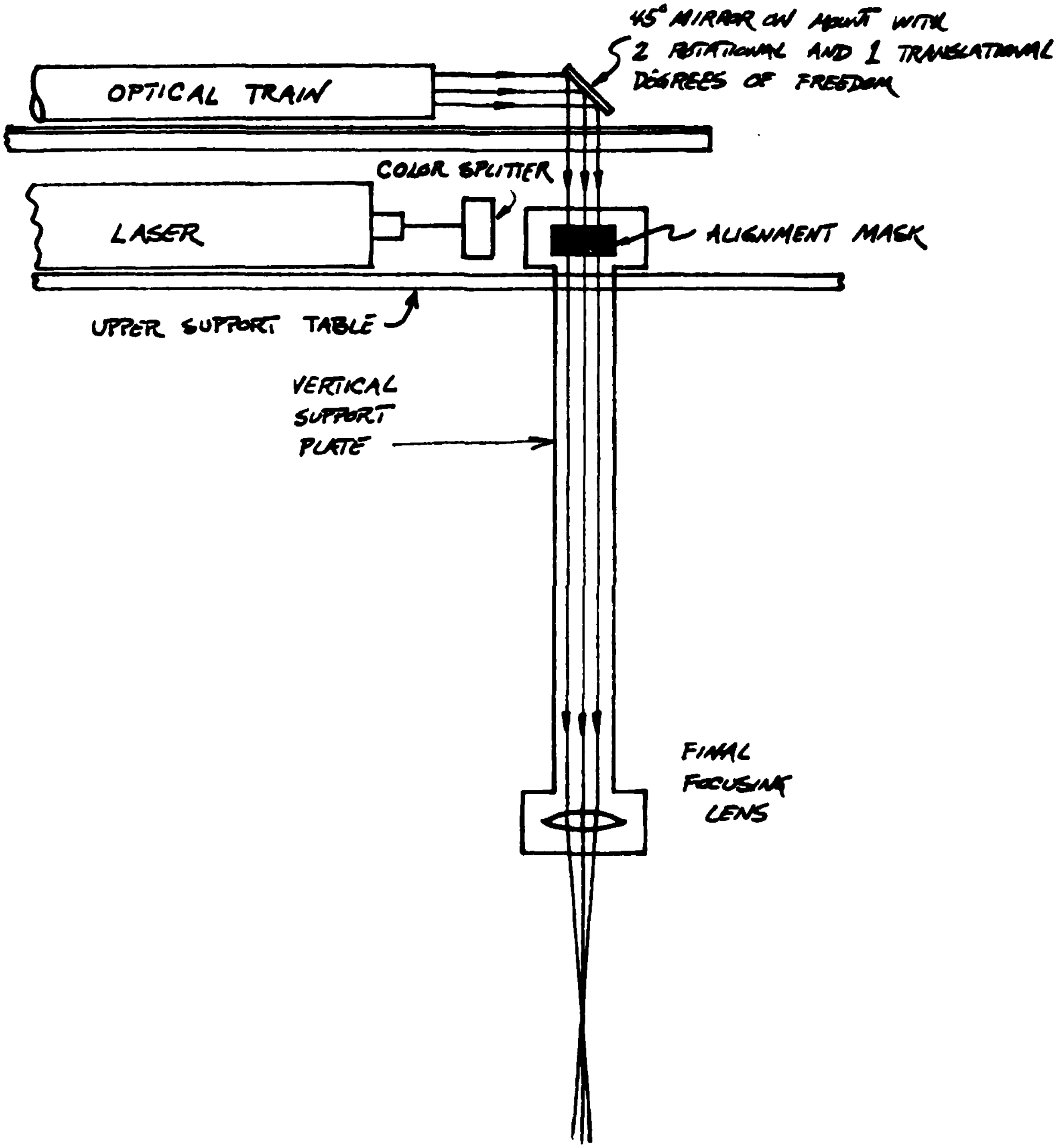


FIGURE 10. DETAILS OF THE 90° TURN

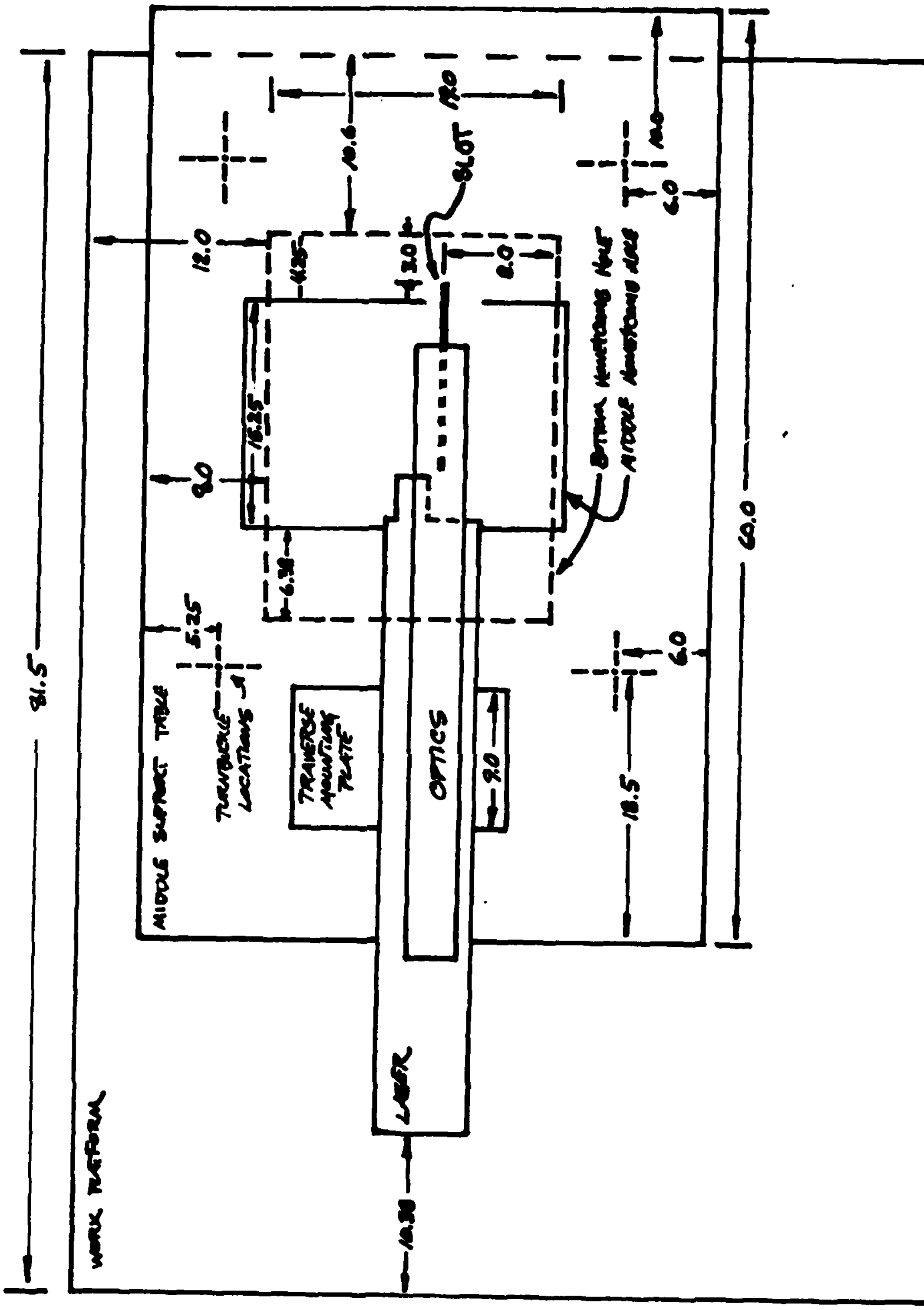


FIGURE 11. STRUCTURE AND SUPPORT DETAILS, TOP VIEW

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FINAL REPORT

ELECTROMYOGRAPHIC CORRELATES OF FLIGHT-CREW PERFORMANCE

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Date:	September 11, 1979
Contract No:	F49620-79-C-0038

ELECTROMYOGRAPHIC CORRELATES

OF

FLIGHT-CREW PERFORMANCE

by

J.R. Lakey

ABSTRACT

A tutorial review is presented concerning the application of electromyographic techniques to flight-crew assessment problems. Basic physiologic and human-factors perspectives are reviewed to furnish acquaintance with underlying assumptions of such application. It is suggested that current clinical electromyography provides an easily adaptable technology for initial application attempts.
A survey of that electromyographic research related to *performance* factors reveals remarkable consistent findings that encourages the application of these techniques to flight workload and fatigue problems of immediate Air Force concern. General recommendations are offered toward the successful development of this application.

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I. INTRODUCTION:

Evaluation of human factors in long-range flight crew performance has primarily relied on subjective fatigue ratings (Hartman, 1971). While such data has proved its value in the identification of potential crew-performance deficients, more objective physiologic measures are sought to provide concurrent verification of reported performance capacity. While some success has been achieved with various urinary metabolite analyses (Hartman, Ellis, Garcia & Bollinger, 1977), numerous problems have been encountered with in-flight sample collection (e.g., Storm & Hapenney, 1976). As a result, more reliable physiologic measures are presently sought in the area of general electrophysiology (O'Donnell & Hartman, in press). Certain of these measures are thought more adaptable to field and flight data collection than others (Wierwille & Williges, 1978, Table 9). Certain of these measures appear to provide more valid indices of crew-performance capacity than others (Wierwille & Williges, 1978, Table 6). Based on a review of the pertinent research literature, it is the contention of this report that electromyographic (EMG) recordings are likely to yield a valid, reliable, and immediately feasible index of significant crew-performance factors in long-range flight missions. Further, it is proposed that EMG recordings are likely to provide a meaningful correlate with those human factors involved in high-performance flight missions. It is not proposed that EMG recordings are a sufficient sole index of relevant human factors; however, it is proposed that such measures should be included in any physiologic battery of performance capacity assessment.

II. OBJECTIVES:

The objectives of this project were:

(1) To survey the research literature concerning electromyographic correlates of flight-related performance.

(2) To develope a tutorial review of possible electromyographic indices of performance for use by division personnel.

(3) To evaluate the adequacy of present knowledge and the need for appropriate electromyographic research for the development of field- and flight-compatible assessment technology.

III. PHYSIOLOGICAL PERSPECTIVE:

The current perspective of physiologic correlates of human performance is heavily influenced by Cannon's (1932) neurophysiological model and Selye's (1956) endocrinological model. In short, these models specify that the central nervous system perceives an adjustive demand, a "stressor" that disrupts the body's normal homeostatic state governed by the autonomic parasympathetic nervous system. Often this perception is accompanied by a rapid low-amplitude beta electroencephalographic (EEG) pattern and other short-term "orienting responses" (Sokolov, 1963). There follows the general mobilization response characterized by increased catecholaminergic neural activity and activation of the autonomic sympathetic nervous system. Observable components of this "stress" reaction include increased general muscle tonus (EMG levels) and resulting tremor, increased perspiration (increased skin conductance or decreased skin resistance or galvanic skin response)[1], increased heart rate and beat irregularities, increased blood pressure and decreased skin-surface temperature, increased breathing rate, pupillary dilation, increased epinephrine and norepinephrine secretion by the adrenal medulla gland, and increased ACTH secretion by the pituitary gland. With continued activation of this "alarm" system, there follows a longer-term endocrinological "resistance stage" denoted by increased secretion of the more than fifty corticosteroids--but in particular hydrocortisone (cortisol)--that affect cellular metabolism of water and electrolytes, carbohydrate, fat, and protein as well as inflammatory tissue defenses. Prolongation of these little-understood endocrine responses can result in the "exhaustion stage," ideopathic organ breakdown, and eventual death.

IV. HUMAN-FACTORS PERSPECTIVE:

Human-factors specialists have approached the man-machine performance question with the basic physical concepts of intensity, time, and more recently phase as typically applied by engineers to any dynamic energy system. Intensity effects are variously referred to as sympathetic arousal or activation, or just arousal or activation, alertness, or effort when its voluntary origin is emphasized. Intensity, whatever the pseudonym, is thought to be and is usually indexed by subjective

1. See Hassett (1978, Chapt. 4) for a discussion of the appropriate measures of electrodermal activity as well as general electrophysiology.

estimate, performance, and electrophysiologic measures. Temporal effects--variations of intensity over time--are variously referred to as warmup, adaptation, habituation, practice, or fatigue depending on the period of concern. These temporal variations are usually indexed by the same subjective, performance, and electrophysiologic measures now plotted over time, but often with the addition of endocrinologic metabolite analyses for longer-term fatigue effects. Recently these temporal effects have been related to organismic circadian rhythms or diurnal variations for the appreciation of phasic effects (e.g., Hartman, Hale, Harris & Sanford, 1974). Generally, performance is related to both intensity and time with inverted-U-shaped functions.[2]

In regard to intensity, performance is viewed as a non-specific inverted-U-shaped function of behavioral "arousal." Optimal performance occurs with that intensity level appropriate to the requirements of the task. Performance decrements occur with either bored/fatigued underarousal or emotional overarousal. Although performance is most often presented in terms of quantitative effectiveness (viz., percent-correct), it should be pointed out that qualitatively different errors are to be expected at under-optimal and over-optimal arousal levels. Underarousal errors are likely to be those of under-reaction or omission, signal misses, or the statistical type II category (Broadbent, 1971); overarousal errors are likely to be those of over-reaction or commission, false alarms, or

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2. Given a nonlinear inverted-U-shaped relationship between performance and arousal variables, one should employ nonlinear correlation coefficients (see Glass & Stanley, 1970, pp. 150f).

the statistical type I category (Simonov, Frolov, Evtushenko & Sviridov, 1977).

In regard to time, performance is also viewed as a general inverted-U-shaped function of behavioral intensity variations over the temporal duration of the task. Optimal performance occurs during the middle portion of the work period. Performance decrements occur earlier before warmup has attained optimal arousal or later after fatigue has eroded arousal to sub-optimal levels. It is assumed that increasing voluntary effort is required to maintain optimal arousal levels against the cumulative effects of fatigue. Both the warmup rise and the fatigue decay of arousal are thought to be exponential processes: as such, one may specify the approximate relationship with performance with the equation,

$$PC = E(1 - e^{-\frac{t}{k_a}}) - E(1 - e^{-\frac{t}{k_f}}) + k_d \sin .083\pi(t + \Delta t),$$

where PC stands for "performance capacity" (optimal performance arousal) as related to t or "time" in hours with E or voluntary "effort" as the one free parameter. The first term of the equation represents "arousal," the second term represents "fatigue," and the third term represents "diurnal" variations. k_a and k_f are experimentally identified time-constants for the arousal onset and fatigue decay processes respectively with the latter obviously much larger than the former. k_d is the maximum effect found with diurnal variation with Δt the time since the normal hour of awaking. This mathematical model produces a rapidly increasing function to optimal arousal level followed by a slow decline as fatigue effects set in. Step increments of effort are required to counter fatigue and maintain optimal arousal thus producing the performance oscillations found in sustained work (e.g., Kennedy, 1953). The function increases more rapidly and declines more slowly during normal wakeful periods while the reverse is true during normal sleep periods.

Despite its shortcomings (Gartner & Murphy, 1976), this model relates performance, voluntary effort, involuntary fatigue, and diurnal variations in an explicit fashion, at least to the extent allowing crude mathematical expression. Certainly this model retains substantial influence in modern human-factors perspective. In this context, the subsequent literature review will reveal that many authors have proposed general muscle tonus to be a valid and reliable measure of voluntary effort and the single free parameter of the dynamic model.

V. APPLIED ELECTROMYOGRAPHY:

Despite an early history in experimental psychology, the increasing bulk of recent developments in electromyography originate in the clinical areas (Goldstein, 1972; Basmajian, 1974). Indeed, a widespread application in modern behavioral medicine involves the use of EMG biofeedback, typically from the forehead muscles, to assist with the attainment of lowered-arousal states through general muscular and emotional relaxation (Basmajian, 1979). The forehead muscles are a popular recording site due to their general lack of involvement in purposive movement. This site also offers the advantage of being relatively free from breathing and ECG artifacts. Human-factors specialists should be aware of the readily available technology and the similar theoretical perspective found in contemporary clinical applications.

VI. LITERATURE REVIEW:

The observation that "mental effort" is associated with an increment of general muscle tonus was often made by early investigators (e.g., Jacobson, 1932,1940; Davis, 1939; Hadley, 1940). Courts (1942) reviewed the earlier work concluding: (1) following an initial spurt at task onset "continuous mental or muscular work is accompanied by an increase in muscle tension..." (p.355), (2) increasing difficulty of the mental task yields higher muscle tension levels, and (3) increasing practice with or habituation to the mental task results in relatively lower muscle tension levels. For the most part, these generalizations have remained after 37 years of intervening research.

Kennedy & Travis (1947,1948) found that higher forehead muscle tonus predicted faster reaction times and more accurate target tracking in a monotonous two-hour simulated flight. They characterized this EMG measure as an able indicator of aircrew "alertness" with lower levels indicative of impaired information processing. Kennedy (1953) later noted that, as their subjects became sleepy, the forehead EMG began to slowly oscillate between higher levels of intermittent alertness and progressively lower levels of inalertness and sleep. This oscillatory effect may have been related to an "alertness indicator" that sounded a loud warning when EMG levels dropped too low.

Ryan, Cottrell & Bitterman (1950,1951) proposed muscle tonus to be an objective index of voluntary "effort" following the lead of earlier work. In support of this contention, they found general EMG levels, especially those from the head and neck, to increase with more difficult reading conditions that presumedly required greater effort.

Woodworth & Schlosberg (1954, pp.173f) summarized the preceeding studies in their textbook of experimental psychology. With bold pedagogy and no supporting data they stated, while forehead EMG "can furnish an excellent indication of the general level of alertness" (p.178), "the neck muscles are the key indicators of the general level of muscle tonus" (p.174). This statement influenced a generation of research efforts.

The early fifties saw the McGill University group under the leadership of Robert Malmo initiate a research program concerning EMG correlates of performance that was to continue throughout the decade. Many of these studies utilized RCAF personnel with some interest in flight-crew performance. Smith, Malmo & Shagass (1953) found evidence suggesting that facial (chin and forehead) EMG levels varied with attentive listening. In a follow-up study, Wallerstein (1954) recorded from forehead, chin, and both forearm extensors to find rising potentials during the course of listening in only the facial areas. This EMG increment was more marked for highly interesting story materials. For less interesting essay materials, steady EMG decrements occurred as the subject became sleepy and actually fell asleep.

Smith (1953) and Bartoshuk (1954,1955ab) found a progressive monotonic increase in chin, active and passive arm EMGs during the course of mirror-tracing tasks. Errors tended to be inversely related to these levels. The latter author emphasized the variations of EMG level with motivation and commensurate effort for accurate performance.

Surwillo (1956) measured forehead, active and passive wrist EMG levels during 2½ min. visual tracking tasks of differing difficulty. Again, a progressive increase was found in all muscle potentials during the course of the task. Relatively higher EMG levels were associated with the more difficult task. Stennett (1957) measured only active and passive wrist EMG levels during a 2 min. auditory tracking task with differing degrees of incentive for good performances. The usual progressive EMG level increase was obtained over the course of the task with higher relative levels occurring with the greater incentive. Both studies appeared to manipulate subject effort for the production of higher EMG levels.

Malmo (1957,1958) summarized many of the McGill findings in terms of the inverted-U-shaped relationship between performance and arousal and effort as indicated by general muscle tonus.

Robert Eason (1959ab,1960) soon thereafter began a research program at the Navy Electronics Laboratory and San Diego State College that was to continue to the mid-sixties. This work was more specifically directed toward the utility of passive muscle tonus as an index of subjective effort as well as muscular fatigue in flight-related situations. These initial studies found EMG levels in both active and passive arm muscles to progressively increase during sustained isometric contraction. Subjective estimates of the amount of effort exerted during the contraction paralleled the EMG levels.

Eason & White (1960) provided the basic research paradigm to be used by most of the subsequent studies. They recorded from neck, back, shoulder, and arm muscles during successive 1 min. rotary pursuit trials separated by 0-40 sec. rest periods. The most fatiguing no-rest condition produced a progressively increasing EMG level from one trial to the next to maintain essentially constant time-on-target; the least fatiguing 40-sec.-rest condition produced the reverse effects with progressively increasing time-on-target and a relatively constant EMG level. Intermediate rest durations produced concomitant rises in both EMG level and performance accuracy. The authors proposed a "two-factor" interpretation of these results: EMG level was a function of both fatigue, as demonstrated, and effort, the subject of their next study.

Eason & White (1961) found EMG levels to parallel increased voluntary effort toward higher time-on-target goals, to increase exponentially with greater task difficulty, thus required effort, manipulated by smaller target size, and to increase linearly with increased workload adjusted by weights suspended from the tracking arm. The neck muscle EMG was found to be "the best single indicator of effort, and as good an indicator as the tension level of the combined muscles" (p.369). The standing head-down rigid posture required of subjects in all of these rotary pursuit studies may have affected this result (see Fig. 1, p.334). In another study of effort effects, Eason & Branks (1963) recorded from forehead, neck, back, and forearm muscles during rotary pursuit under different conditions of payoff or incentive for good performance. They found higher EMG levels in the higher incentive-for-effort conditions for all muscles save the forehead. In contrast to the reports of other laboratories, the forehead EMG was remarkably constant across all incentive conditions--indeed even over the 3½ min. duration of the pursuit task.

Eason (1963) found no effect of eight days of practice on neck, back, upper arm, and forearm EMG levels or patterns despite marked performance improvements in time-on-target. The neck again produced the most consistent levels and patterns of variations: neck tension progressively decreased from one 3½ min. trial to the next of a 45 min. daily session while tracking performance improved. This same EMG result was obtained during subsequent daily sessions without alteration of absolute level despite general performance improvements. During the 3½ min. trial, neck EMG levels increased for the smallest, most difficult targets and decreased for the larger, less difficult targets. Performance always deteriorated.

Changing to a new experimental paradigm, Eason, Harter & Storm (1964) used seated subjects who memorized nonsense syllables under different conditions of arm tension induced by squeezing a hand dynamometer or lifting weights. Neck EMG levels were found to progressively increase within 2 min. trials, but to gradually decrease from one trial to the next during the one-hour session. Concurrent skin conductance and heart rate measures generally decreased both within trials and from one trial to the next. Memorization performance increased both within and between trials. An unexpected and unexplained result found neck EMG levels to first decrease then increase with higher induced-tension levels of the arm.

Eason, Beardshall & Jaffee (1965) used seated subjects in a one-hour vigilance task detecting visual signals that occurred at rates of 1/30 sec. or 1/2 min. Neck EMG level increased over the course of the vigil while detection performance deteriorated due to increasing missed signals. False alarm detections were virtually absent throughout the vigil. A composite facial EMG taken around the eye was essentially constant throughout the vigil. Concurrent skin conductance measures increased while heart rate was also unaffected by time-at-vigil. No differences were found between the two signal presentation rates. These results were somewhat atypical of many vigilance studies (see Mackie, 1977) suggesting non-monotonous conditions and highly motivated subjects.

In France, Laville & Wisner (1965) also found a progressive neck EMG increase over a two-hour work period involving a rapid-precision task. Concurrent heart rate measures were unaffected. Wisner (1973) later replicated these results.

Stern (1966) employed a one-hour vigilance task detecting visual signals--the movement of a small point of light on an oscilloscope face. Unfortunately the use of this particular signal confounded detection performance since it was subject to the autokinetic phenomenon. As might have been anticipated, correct detections decreased and false alarms increased over the course of the vigil. For frequent 1/30 sec. signal presentations, both forehead and neck EMG levels were relatively constant during the vigil; for infrequent 1/1 min. signal presentations, these same potentials initially increased, then decreased to a mid-vigil low, only to increase again toward the end of the vigil. This latter result was largely due to the autokinetic phenomenon. Basal skin resistance rose (conductance fell) while heart and respiration rates were constant over the vigil.

O'Hanlon & Horvath (1969) reported serum norepinephrine and free-fatty acid levels to parallel neck EMG increments over the course of a vigil. O'Hanlon (1970) later found neck EMG levels to increase during a one-hour vigil for the detection of difficult (dim) visual signals, but to remain relatively constant for easy (bright) visual signals occurring at 1/3 sec. Neck EMG levels were consistently higher for the more difficult task. Correct detections decreased during the first 45 min. of the vigil, then increased during the last 15 min. False alarms generally declined over the vigil, more so for the difficult task. Serum epinephrine level and respiration rate fell while GSR frequency and heart rate variability rose over the course of the vigil.

Dureman & Boden (1972) measured the neck EMG levels of driving-school students during a 2-hour simulated car driving task. Neck EMG levels tended to increase over the duration of the task, but this trend was not significantly significant. Concurrent fatigue ratings, steering errors, and skin resistance measurements also increased while heart and respiration rates declined over the task.

Innes (1973) measured neck EMG levels in a simulated flight-vigilance situation lasting 1½ hours. He found a marked progressive EMG increase over the course of the vigil along with ECG sinus arryhthmias and subjective ratings of fatigue increments. Correct signal detections increased to mid-vigil and thereafter decreased; false alarm errors decreased over the vigil.

Returning to short-duration tasks and more transient-change EMG phenomena, Spyker, Stackhouse, Khalafalla & McLane (1971) monitored forearm EMG levels during a simulated flight task combining tracking and detection. Correlations between EMG levels and performance measures were significant and relatively high--approaching +.50. Certain features of ECG and respiration records also produced high significant correlations with performance measures.

Stackhouse (1976) measured both forehead and forearm EMG levels in another flight-simulated task. Standard deviation of forehead EMG, mean of forearm EMG level, and standard deviation of forearm EMG zero-crossings were found to be the most predictive and highly correlated features of performance along with ECG T-interval and ECG R-amplitude.

Carriero (1977) utilized forearm EMG in a unique study that focused on the averaged 10-sec. response following the presentation of a visual signal for detection. Generally, the EMG level rose during this observation interval, but the increment was significantly steeper when the subsequent detection report was to be incorrect.

<u>Summary</u>:

Courts' (1942) conclusions that prefaced this section are largely substantiated by review of succeeding research. First, EMG levels are consistently found to progressively rise over the course of both short and long duration tasks, whether the tasks require physical or mental exertion or both--provided that the subject can stay awake and that the task is continuous. A progressive EMG decline is found as a subject falls alseep (Kennedy & Travis, 1947,1948; Wallerstein, 1954); indeed, EMG records are characterized as "the most reliable indicator" of sleep stages (Dement, 1976, p.90). A progressive EMG decline is also found from one trial to the next in a series separated by short rest periods (Eason & White, 1960, Figs.3&5; Eason & Branks, 1963, Fig.5; Eason, 1963, Fig.9; Eason, Harter & Storm, 1964). These effects have been explained as "a general adaptation effect to the experimental situation each day" (Eason, 1963, p.316). It should be reiterated that EMG levels progressively increase within each performance trial in all these studies.

Second, EMG levels are consistently found to be relatively higher in more difficult tasks (Ryan <u>et al</u>., 1950; Surwillo, 1956; Eason & White, 1961; O'Hanlon, 1970).

Third, lower EMG levels seem to appear with task habituation in the trial-to-trial effects found by the Eason group--at least that is their explanation. While this trial-to-trial effect might also be termed a short-term or warm-up practice effect, long-term EMG declines with repeated daily practice have not been obtained (Eason, 1963).

As proposed by the earliest authors, the explanation for these EMG variations still centers about the concept of voluntary "effort": EMG levels rise when one is simply asked to "try harder" (Eason & White, 1961), when one is given greater incentive to "try harder" (Stennett, 1957; Eason & Branks, 1963), when task difficulty demands that one "try harder" (Ryan _et al_., 1950; Surwillo, 1956; Eason & White, 1961; O'Hanlon, 1970), or when bodily fatigue necessitates that we "try harder" to continue functioning (Eason, Beardshall & Jaffee, 1964; Laville & Wisner, 1965; O'Hanlon, 1970; Dureman & Boden, 1972; Innes, 1973). The alternative explanation using involuntary "arousal" is not supported by these last data that show EMG levels to rise while other physiologic indicators of "arousal" fall (see O'Hanlon, 1970). As such, EMG levels would be a measure of the mind's will if not the thought process _per se_ as proposed by the early Behaviorists (Watson, 1930).

Which single or combined muscle groups provide the best index of general muscle tonus and "effort"? As suggested by Woodworth & Schlosberg (1954), the neck EMG receives the endorsement of the largest number of studies: about a dozen different reports find meaningful neck-tension variations correlated with performance aspects. Several studies compare various recording sites to conclude superiority of the neck EMG in this regard (Niedever, 1959; Eason & White, 1961; Eason, 1963; Eason, Beardshall & Jaffee, 1964).

Nonetheless, both active and passive arm-muscle EMGs have also produced good correlations with performance in the reviewed studies (Malmo, 1957,1958; Eason, 1960; Eason & White, 1960, 1961; Eason & Branks, 1963; Spyker et al., 1971; Stackhouse, 1976; Carriero, 1977) as well as other studies not reviewed (Voas, 1952; Nidever, 1959; Balshan, 1962).

The head-muscle EMGs have further produced correlations with performance (Kennedy & Travis, 1947,1948; Wallerstein, 1954; Surwillo, 1956; Nidever, 1959; Stackhouse, 1976) although negative results have been obtained as well (Eason & Branks, 1963). This is somewhat surprising in view of the extensive use of head-muscle EMGs in other areas of research (Dement, 1976; Basmajian, 1979; Ekman & Oster, 1979).

In those studies that included concurrent measurement of other physiologic variables, there are minor but consistent indications that high EMG levels may be associated with high heart-rate variability (O'Hanlon, 1970; Spyker et al., 1971; Innes, 1973; Stackhouse, 1976) and low respiration rates (O'Hanlon, 1970; Spyker et al., 1971; Dureman & Boden, 1972).

In conclusion, it can be simply stated that available data suggest that neck-EMG levels offer a possible measure of performance effort.

VII. RECOMMENDATIONS:

(1) EMG measurements should be included in any physiologic assessment battery concerned with flight-crew effort, fatigue, inalertness, sleep, or related performance factors.

(2) If possible, simultaneous EMG records should be obtained from the neck, arm, and forehead muscles, listed in the order of desirability for inclusion in an assessment battery.

(3) If possible, simultaneous ECG and respiration records should be obtained to aid in the evaluation of EMG data.

(4) EMG records should be subjected to more sophisticated data-analysis techniques, for example, spectral analysis, in addition to simple integrated-level variations across time.

(5) Further research should be directed toward identication of EMG correlates of crew performance in higher-fidelity flight-simulated situations.

(6) Further research should be directed toward transient EMG responses in addition to progressive EMG responses.

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FINAL REPORT

INVESTIGATION OF TIME-TO-GO ALGORITHMS FOR AIR-TO-AIR MISSILES

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by

Gordon K. F. Lee

ABSTRACT

The design of optimal controllers for air-to-air missiles has resulted in much interest. Many control laws require knowledge of a good estimate of the time-to-go (tgo) before intercept. This report presents an algorithm for estimating time-to-go using the current relative position and velocity characteristics of the missile and target. By constructing an objective function representing terminal miss distance, one is able to obtain an iterative scheme for estimating tgo. Simulation studies using a smart target algorithm and this methodology have yielded good results which show improvement over conventional algorithms for estimating tgo. A comparative investigation of the methodology developed in this report with other algorithms is presented.

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Special thanks is due to Lt Tom Riggs, Jr for his stimulating discussions on the air-to-air intercept problem. Finally, the author would like to extend his appreciation to Lt Paul Vergez for his time and effort in familiarizing him with the air-to-air simulation programming package.

I. INTRODUCTION:

The air-to-air intercept problem can be formulated in many ways. The primary objective of this problem is to minimize terminal miss-distance (hit the target) under unknown target maneuvers. Secondary objectives include using minimal control effort over the entire scenario, minimizing time, and minimizing the state vectors representing relative positions and velocities between missile and target over all time. Overall constraints in developing methodologies that satisfy such design objectives should be real time or near real time computation and easy implementation.

Several models have been proposed [1,2,5,6] for the air-to-air scenario. This report will concentrate on a linearized model based upon aerodynamic properties. With the air-to-air models so chosen, the control objective is to choose a missile command to eventually hit a maneuvering target.

The nominal approach to choosing such a missile command is proportional navigation. While this method is relatively easy to implement and works well for simple scenarios, many assumptions are necessary for its derivation [4]. In particular, proportional navigation requires the following assumptions: the target acceleration is zero, the missile's accelerations are completely controllable, the line-of-sight angles are small over the entire scenario and most importantly, the range rate is constant. These assumptions result in less than acceptable trajectories for complex flights.

Section III presents the basic linearized system model and the optimal guidance control law. Some of the assumptions are then removed resulting in a suboptimal guidance law. A necessary parameter in implementing such a guidance law is the time-to-go before intercept. Section IV develops the algorithm for estimating time-to-go. A comparison of this methodology with other formulations through simulation results is given in Section V, while the derivation of the estimation of tgo is developed in the appendix.

The methodology developed has the appealing characteristics of being computationally attractive to implement as well as comparable (and better in certain flight maneuvers) to existing time-to-go estimates. A further attractive feature of this methodology is that, as it is based upon optimal control theory, the algorithm gives some insight into the effects of various performance indices on the overall terminal miss-distance objectives.

II. OBJECTIVES:

The objectives of this research effort were the following:

1. To develop estimation algorithms for the time-to-go before intercept parameter.

2. To study the inner launch boundaries generated by such algorithms and compare these results with existing methods.

3. To implement the most attractive estimator algorithm (in terms of computation versus miss-distance) into the existing air-to-air simulation program.

III. PROBLEM DEVELOPMENT:

Before developing the linearized optimal control law, the basic notion used in this report is in order. Let $(\underline{\ })$ denote a column vector, $(\underline{\ })^T$ represent its transpose, I denote the identity matrix, and $(\ )^{-1}$ denote a matrix inverse.

Consider the following dynamics representing a linearized time-invariant air-to-air scenario:

$$\begin{aligned} \dot{\underline{x}}(t) &= \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix} \underline{x}(t) + \begin{bmatrix} 0 \\ I \end{bmatrix} \underline{u}(t) \\ &= A\underline{x}(t) + B\underline{u}(t) \end{aligned} \tag{1}$$

where $\underline{x}(t) = \begin{bmatrix} \underline{x}_p(t) \\ \underline{x}_v(t) \end{bmatrix}$ represents the augmented relative position vector $\underline{x}_p(t)$ and relative velocity vector $\underline{X}_V$ (t) in x, y, and z missile body coordinates (see Figure 1). The vector $\underline{u}$ (t) represents the commanded acceleration control vector. In representing the air-to-air scenario by (1), it is assumed that $\underline{u}$ (t) is a control vector, i.e., that (1) is completely controllable. This is, in fact, not true and this assumption will be relaxed later.

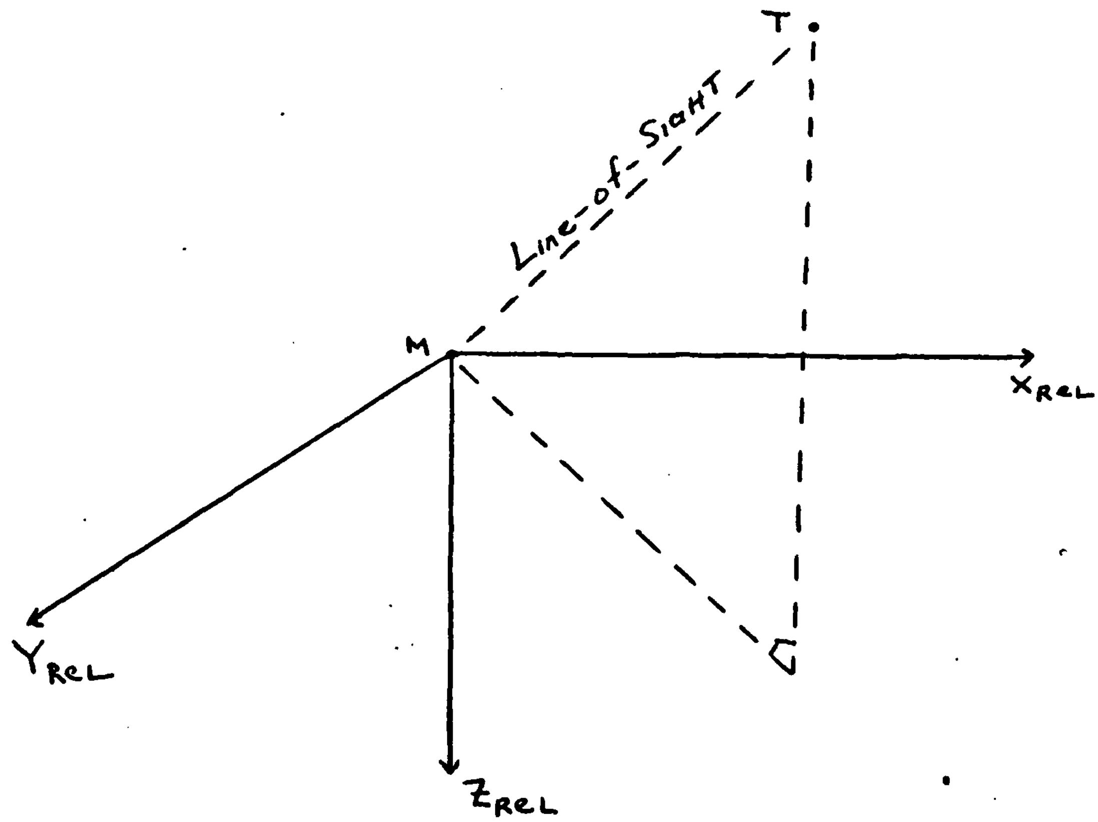

FIGURE 1: MISSILE AND TARGET USING RELATIVE COORDINATES

Suppose it is desired to hit the target with minimal control effort. A representative cost functional for this performance objective may be:

$$J = \underline{x}^T(t_f) S_f \, \underline{x}(t_f) + \frac{1}{2}\int_{t_0}^{t_f} \underline{u}^T(t) R \underline{u}(t) \, dt \tag{2}$$

where $S_f = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}$, $R = \mathrm{diag}\,(r)$,

t_o = initial time and t_f = final time.

Direct optimization of (2) with respect to the control vector $\underline{u}$ (t) can be accomplished by constructing the Hamiltonian [3]:

$$H = \frac{1}{2} \underline{u}^T(t) R \underline{u}(t) + \underline{\lambda}^T(t) \left(A \underline{x}(t) + B \underline{u}(t) \right) \tag{3}$$

By applying a singular pertubation on H, one finds the optimal control law is given by:

$$\underline{u}^*(t) = -R^{-1} B^T \underline{\lambda}(t) \tag{4}$$

where $\underline{\lambda}$(t) is the co-state vector. By assuming t_f, t_o, $\underline{x}$ (t_o), and $\underline{\lambda}$ (t_f) are given, the optimal control law is usually solved via a two-point boundary valued method (this requires integration forward and backwards in time). If t_f is unknown (which is the case for the air-to-air problem), a term due to the transversality condition on unspecified final time is added to (3).

Under the assumption that t_f is given or can be accurately estimated, due to the simplicity of R, B, A, and S_f, a direct solution can be obtained to (3) resulting in the optimal control law (with $r=0$):

$$\underline{u}^* (t) = - K \underline{x} (t) \tag{5}$$

where

$$K = \frac{3}{tgo^2} \left[I \;\vdots\; tgo \; I \right] \tag{6}$$

and tgo = t_f - t = time-to-go before intercept. Equation (5) represents an optimal control law if tgo is known, if (1) is controllable, and if $\underline{u}$ (t) is the control vector (i.e., the target acceleration is known or identically zero). As (1) is not controllable, (5) must be modified resulting in a suboptimal control law. This law can be further improved if an accurate estimate of time-to-go is obtained. This is the main contribution of this report. Inclusion of estimates of target acceleration is an area of future study.

IV. ESTIMATION OF TIME-TO-GO

In order to estimate time-to-go, one may optimize (2) with respect to tgo. However this results in much computation. For analysis purposes, it is desirable to estimate tgo using the following design objective:

$$J_{tgo} = \underline{x}^T(t_f)\, S_f\, \underline{x}(t_f) + q \left(\int_0^{tgo} d\tau \right)^2 \qquad (7)$$

where q is a weighting factor on time. Note that (7) represents a performance criterion based upon terminal miss-distance and time-to-go. Optimization of (7) with respect to tgo results in an estimate of time-to-go which can then be used in (6).

To minimize (7) with respect to tgo, we note that:

$$\underline{x}(t_f) = e^{\bar{A}(t_f - t)}\, \underline{x}(t) + \int_t^{t_f} e^{\bar{A}(t_f - \tau)}\, B\, \underline{C}(\tau)\, d\tau \qquad (8)$$

where A represents the closed-loop system matrix using an appropriate feedback control law and $\underline{C}$ (t) represents a disturbance input. We noted earlier that (5) assumed a completley controllable system. As present air-to-air missiles do not have a commanded control in the x-direction, a modification of (5) is necessary.

Let

$$\underline{u}(t) = -GK\,\underline{x}(t) \tag{9}$$

$$\text{Where } G = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{10}$$

Note that (9) represents a suboptimal controller to (2) in that the relative position and velocity variables in the x-direction are not used. In order to compensate for this suboptimality when estimating tgo, the controller of (9) can be modified as:

$$\underline{u}(t) = -GK\,\underline{x}(t) - \underline{u}_m \tag{11}$$

where $\underline{u}_m = (f_{nx}\ 0\ \ 0)^T$ represents a measurable achieved missile acceleration in the x-direction. It will be assumed that f_{nx} is a constant, independent of time, although this may not be true for all scenarios.

Both controllers (9) and (11) will be studied for estimating tgo via (7). The resulting tgo found will then be used in the guidance control law based upon (5) and (6) developed by Riggs [4]. The closed-loop system matrix using either (9) or (11) becomes:

$$\bar{A} = A - BGK \tag{12}$$

while $\underline{C}(t)$, the disturbance matrix, is identically zero for (9) but equal to $\underline{u}_m$ for (11).

Substitution of (8) into (7) assuming (12) finds:

$$\begin{aligned} J_{tgo} = {} & \underline{x}^T(t)\, e^{\bar{A}^T t_{go}} S_f\, e^{\bar{A} t_{go}}\, \underline{x}(t) + \\ & 2\,\underline{x}^T(t)\, e^{\bar{A}^T t_{go}} S_f \int_0^{t_{go}} e^{\bar{A}\tau} d\tau\, B\,\underline{C} + \\ & \underline{C}^T B^T \int_0^{t_{go}} e^{\bar{A}^T \tau} d\tau\, S_f \int_0^{t_{go}} e^{\bar{A}\tau} d\tau\, B\,\underline{C} + \\ & q\, t_{go}^2 \end{aligned} \tag{13}$$

where $\underline{C}$ (t) is assumed constant and t corresponds to the present time.

Direct minimization of (13) with respect to tgo finds:

$$\frac{\partial}{\partial t_{go}} J_{t_{go}} = 2\,\underline{x}^T(t)\, e^{\bar{A}^T t_{go}} S_f \frac{\partial}{\partial t_{go}}\left(e^{\bar{A} t_{go}}\right)\underline{x}(t)$$

$$+ 2\,\underline{x}^T(t)\left[\frac{\partial}{\partial t_{go}}\left(e^{\bar{A}^T t_{go}}\right) S_f \int_0^{t_{go}} e^{\bar{A}\tau} d\tau\right.$$

$$\left. + e^{\bar{A}^T t_{go}} S_f \left\{ e^{\bar{A} t_{go}} + \int_0^{t_{go}} \frac{\partial}{\partial t_{go}}\left(e^{\bar{A}\tau}\right) d\tau\right\}\right] B\,\underline{c}$$

$$+ 2\,\underline{c}^T B^T \int_0^{t_{go}} e^{\bar{A}^T \tau} d\tau\, S_f \left[e^{\bar{A} t_{go}} + \right.$$

$$\left.\int_0^{t_{go}} \frac{\partial}{\partial t_{go}}\left(e^{\bar{A}\tau}\right) d\tau\right] B\,\underline{c} + 2 q\, t_{go}$$

$$= 2\left\{ \underline{x}^T(t)\, e^{\bar{A}^T t_{go}} S_f \frac{\partial}{\partial t_{go}}\left(e^{\bar{A} t_{go}}\right)\underline{x}(t)\right.$$

$$+ \underline{x}^T(t) \frac{\partial}{\partial t_{go}}\left(e^{\bar{A}^T t_{go}}\right) S_f \int_0^{t_{go}} e^{\bar{A}\tau} d\tau\, B\,\underline{c}$$

$$+ \underline{x}^T(t)\, e^{\bar{A}^T t_{go}} S_f\, e^{\bar{A} t_{go}} B\,\underline{c} +$$

$$\underline{x}^T(t)\, e^{\bar{A}^T t_{go}} S_f \int_0^{t_{go}} \frac{\partial}{\partial t_{go}}\left(e^{\bar{A}\tau}\right) d\tau\, B\,\underline{c}$$

$$+ \underline{c}^T B^T \int_0^{t_{go}} e^{\bar{A}^T \tau} d\tau\, S_f\, e^{\bar{A} t_{go}} B\,\underline{c}$$

$$+ \underline{c}^T B^T \int_0^{t_{go}} e^{\bar{A}^T \tau} d\tau\, S_f \int_0^{t_{go}} \frac{\partial}{\partial t_{go}}\left(e^{\bar{A}\tau}\right) d\tau\, B\,\underline{c}$$

$$\left. + q\, t_{go}\right\} \qquad (14)$$

The weighting q is normally chosen so that equal importance is placed on each term in (7). Equating (14) to zero leads to either a first order or third order polynomial in tgo which can be solved at each iteration. When $\underline{c} = 0$, this leads directly to the following estimate of tgo (see appendix):

$$\hat{t}go = - \frac{\underline{x}_p^T(t)\, D\, F\, \underline{x}_v(t)}{(\underline{x}_v^T(t)\, F^T F\, \underline{x}_v(t) + q)} \qquad (15)$$

$$\text{where } D = \begin{bmatrix} 1 & 0 & 0 \\ 0 & d & 0 \\ 0 & 0 & d \end{bmatrix}, \qquad F = \begin{bmatrix} 1 & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & f \end{bmatrix},$$

$$d = e^{-3/2} \cos\left(\frac{\sqrt{3}}{2}\right) + \sqrt{3}\, e^{-3/2} \sin\left(\frac{\sqrt{3}}{2}\right)$$

and

$$f = \frac{2}{\sqrt{3}}\, e^{-3/2} \sin\left(\frac{\sqrt{3}}{2}\right) \qquad (16)$$

The air-to-air intercept simulation using the estimate of tgo algorithm described by (14) results in the following flow diagram (see Figure 2):

V. SIMULATION RESULTS

Preliminary simulation results illustrated the necessity of a good initial guess of time-to-go. An earlier estimation algorithm developed by Riggs [4] which gave promising results was based upon range R, closing velocity V_c, and off bore-sight angles Bay (angle between missile body acceleration in the x-direction and the line-of sight vector at launch). This estimator was used to generate an initial guess of (14). In particular, the initial guess was chosen as:

$$tgo\ (0) = \frac{2R}{V_c + \sqrt{V_c^2 + 52\, R \cos(Bay)\, g}} \qquad (17)$$

where $g = 32.174\ ft/sec^2$.

Tests were conducted using (9), (11), and (17) with a guidance law developed by Riggs. An off bore-sight angle of 40^0 was chosen in order to compare time-to-go estimation algorithms under complex scenarios. Below is a table of the inner launch boundaries (minimum launch range in which the missile still hits the target) for various yaw aspect angles (angle between the targets velocity vector and the line-of-sight at launch) using the following time-to-go

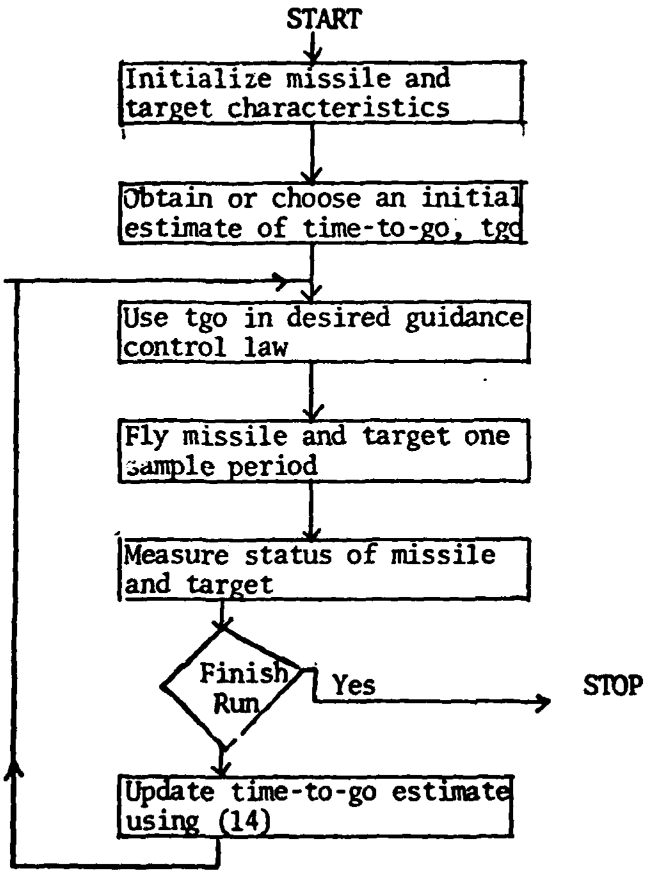

FIGURE 2: AIR-TO-AIR SIMULATION USING NEW ESTIMATE OF TIME-TO-GO ALGORITHM

Estimates:

Pro-Nav: $t_{go} = -\frac{R}{\dot{R}}$ where $\dot{R}$ = range rate is assumed constant

NewG [4] $$t_{go}(i+1) = \frac{2R}{V_c + \sqrt{V_c^2 + 4\tilde{A}R_g}}$$

$$\tilde{A} = \frac{101.4 - 39t - 12t_{go}(i)}{t_{go}(i)}$$

Lee : tgo obtained from (14) and (17). The same guidance control law was used in each case.

Pro-Nav:

Aspect Angle	0	30	60	90	120	150	180
Range	-	-	5750	4250	3000	4750	4750

New G:

Aspect Angle	0	30	60	90	120	150	180
Range	1000	1000	1250	1750	2500	3750	3750

Lee ($q=0$, $\underline{c}=0$):

Aspect Angle	0	30	60	90	120	150	180
Range	1000	1000	1000	1500	2250	4500	4500

Lee ($q=0$, $\underline{c}=\underline{u}_m$):

Aspect Angle	0	30	60	90	120	150	180
Range	1000	1000	1000	1500	2250	4000	4000

Lee ($q \neq 0$, $\underline{c}=0$):

Aspect Angle	0	30	60	90	120	150	180
Range	1000	1000	1000	1500	2250	4250	4500

Lee ($q \neq 0$, $\underline{c}=\underline{u}_m$)

Aspect Angle	0	30	40	90	120	150	180
Range	1000	1000	1000	1500	2250	3750	4000

TABLE 1

From these results, one observes that the methodology developed in this report showed improvement over Pro-Nav and equivalent or better than NEWG at all aspect angles except 150^o and 180^o. The influence of adding the integral of time term in (7) i.e., $q \neq 0$, results in a slight improvement at an aspect angle of 150^o. The influence of adding the disturbance term $\underline{c} = \underline{u}_m$ results in an improvement over NEWG at the higher aspect angles. However the amount of computation is much more than with $\underline{c}=0$ (see Appendix).

Hence using (14) with $q \neq 0$, $\underline{c}=0$ gave the most appealing algorithm for estimating time-to-go, i.e., the algorithm described by (15). One may observe the estimator philosophies behind NEWG and Lee and why these estimator algorithms achieve good results. The estimator NEWG assumes that the acceleration along the line-of-sight has, as its dominant factor, the achieved missile body acceleration in the x-direction, i.e., $\tilde{A}$. Hence the dominant parameter in estimating tgo using NEWG is the missile achieved x-direction acceleration. To compensate for lack of controllability of commanded x-direction control, the methodology developed in this report however uses the influence of lateral and longitudinal commanded controls (through $\underline{x}$ (t_f)). In either case, the algorithms compensate for the uncontrollable command in the x-direction and the assumption of zero target acceleration.

The methodology was also used on a simple 0^o off-bore sight scenario. Table II lists the results along with those of Pro-Nav and NEWG.

Pro-Nav:

Aspect Angle	0	30	60	90	120	150	180
Range	1000	1000	1750	2000	3500	3500	2250

NEWG

Aspect Angle	0	30	60	90	120	150	180
Range	1000	1000	1500	1750	3250	2750	2000

Lee ($q \neq 0$, $\underline{c}=0$)

Aspect Angle	0	30	60	90	120	150	180
Range	1000	1000	1000	1000	2500	3500	2250

TABLE II

VI. RECOMMENDATIONS

An algorithm for estimating time-to-go has been developed using an objective function consisting of terminal miss-distance and time. It was found that the methodology gave promising results under minimal computational burden. By constructing and optimizing the objective functions one is able to observe iteratively how time-to-go changes with respect to current miss-distance and elapsed time. Several areas of study need still be investigated.

First of all, the development of tgo was based under the assumption that the target acceleration was zero. As this is not true, the system dynamics of (1) need be modified which in turn alters the time-to-go estimate.

Secondly, the constraints on missile commanded controls was set to a maximum value above current missile capabilities in the simulation program. Hence the missile's commanded controls found via the time-to-go estimate were above realistic values. By lowering the maximum acceleration level, a degradition in system performance was observed using the current tgo estimator. To improve performance under these missile capacities, work need be done in modifying the weighting factor on time. Presently, as time and terminal miss-distance are weighted equally, the missile tries use maximum acceleration values to achieve minimal time.

Finally, the time-to-go estimator need be investigated using other guidance laws. Included in this investigation should be studies in the tgo estimator under system noise. Such studies should lead to interesting results.

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APPENDIX

In order to evaluate the coefficients of time-to-go, tgo, in (14) it is necessary to compute the following terms: $e^{\bar{A}\,tgo}$, $\int_0^{tgo} e^{\bar{A}t}\,dt$, and $\int_0^{tgo} \frac{\partial}{\partial tgo}\left(e^{\bar{A}t}\right) dt$

The matrix $e^{\bar{A}t}$ can be computed directly using Laplace transforms as:

$$e^{\bar{A}t} = \begin{bmatrix} 1 & 0 & 0 & t & 0 & 0 \\ 0 & \alpha_1(t) & 0 & 0 & \alpha_2(t) & 0 \\ 0 & 0 & \alpha_1(t) & 0 & 0 & \alpha_2(t) \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & \alpha_3(t) & 0 & 0 & \alpha_4(t) & 0 \\ 0 & 0 & \alpha_3(t) & 0 & 0 & \alpha_4(t) \end{bmatrix} \qquad \text{(A1)}$$

where

$$\lambda_1(t) = e^{-(3/2\ tgo)t} \cos\left(\frac{\sqrt{3}}{2tgo}\right)t + \sqrt{3}\, e^{-(3/2\ tgo)t} \sin\left(\frac{\sqrt{3}}{2tgo}\right)t$$

$$\lambda_2(t) = \frac{2tgo}{\sqrt{3}}\ e^{-(3/2\ tgo)t} \sin\left(\frac{\sqrt{3}}{2t_{go}}\right)t$$

$$\lambda_3(t) = \frac{2\sqrt{3}}{tgo}\, e^{-(3/2\ tgo)t} \sin\left(\frac{\sqrt{3}}{2t_{go}}\right)t$$

and

$$\lambda_4(t) = e^{-(3/2\ tgo)t} \cos\left(\frac{\sqrt{3}}{2tgo}\right)t - \sqrt{3}\, e^{-(3/2\ tgo)t} \sin\left(\frac{\sqrt{3}}{2tgo}\right)t \qquad \text{... (A2)}$$

The matrix can also be computed indirectly through a truncated series:

$$e^{\bar{A}\ tgo} = \begin{bmatrix} \Sigma \frac{A_{11}(i)}{i\,!} & \Sigma \frac{A_{12}(i)}{i\,!}\ tgo \\ \Sigma \frac{A_{21}(i)}{i\,!\ tgo} & \Sigma \frac{A_{22}(i)}{i\,!} \end{bmatrix} \qquad \text{... (A3)}$$

where

$$A_{11}(i) = -\ 3G\ (A_{11}\ (i-2) + A_{11}\ (i-1))$$

$$A_{12}(i) = -\ 3G\ (A_{12}\ (i-2) + A_{12}\ (i-1)) \qquad \text{... (A4)}$$

$$A_{21}(i) = 3G\ (2\ A_{11}\ (i-1) + 3A_{11}\ (i-2))$$

$$A_{22}(i) = 3G\ (2\ A_{12}\ (i-1) + 3\ A_{12}\ (i-2)) \qquad i = 3,4,\ldots$$

and

$$A_{11}\ (0) = I \quad A_{11}(1) = 0 \quad A_{11}\ (2) = -\ 3G \qquad \text{...(A5)}$$

$$A_{12}\ (0) = 0 \quad A_{12}(1) = I \quad A_{12}\ (2) = -\ 3G$$

$$A_{21}\ (0) = 0 \quad A_{21}(1) = -3G \quad A_{21}\ (2) = 9G^2$$

$$A_{22}\ (0) = I \quad A_{22}(1) = -\ 3G \quad A_{22}\ (2) = 9G^2 - 3G$$

With $\underline{c} = \underline{u}_m$, the matrices $\int_0^{tgo} e^{\bar{A}t}\,dt$ and $\int_0^{tgo} \frac{\partial}{\partial tgo}(e^{\bar{A}t})\,dt$ need also be computed which adds to further computation. Direct computation analytically using (A1) requires integration by parts. Hence for $\underline{c} = \underline{u}_m$, using (A3) is more attractive. It was found that:

$$\int_0^{t_{go}} e^{\bar{A}\tau}\,d\tau = \begin{bmatrix} \Sigma \frac{V_{11}(i)}{i!} t_{go} & \Sigma \frac{V_{12}(i)}{i!} t_{go}^2 \\ \Sigma \frac{V_{21}(i)}{i!} & \Sigma \frac{V_{22}(i)}{i!} t_{go} \end{bmatrix} \quad \ldots (A6)$$

where $V_{jk}(i)$ has the same form as (A4) with initial conditions:

$$V_{jk}(0) = 0 \quad \forall j,k$$

$$V_{jk}(1) = A_{jk}(0) \quad \ldots (A7)$$

$$V_{jk}(2) = A_{jk}(1)$$

$$\text{Finally } \int_0^{tgo} \frac{\partial}{\partial tgo}(e^{\bar{A}t})\,dt = \begin{bmatrix} \Sigma \frac{W_{11}(i)}{(i+1)!} & \Sigma \frac{W_{12}(i)}{(i+i)!}\ tgc \\ \Sigma \frac{W_{21}(i)}{(i+1)!\ tgo} & \Sigma \frac{W_{22}(i)}{(i+1)!} \end{bmatrix} \quad \ldots (A8)$$

where

$$W_{11}(i) = 6\,G\,A_{11}(i-2) - 3G\,W_{11}(i-2) + 3\,G\,A_{11}(i-1) - 3\,G\,W_{11}(i-1)$$

$$W_{12}(i) = 6\,G\,A_{12}(i-2) - 3\,G\,W_{12}(i-2) + 3\,G\,A_{12}(i-1) - 3G\,W_{12}(i-1)$$

$$W_{21}(i) = -27\,G^2 A_{11}(i-2) + 9\,G^2 W_{11}(i-2) - 18\,G^2 A_{11}(i-1) + 9\,G^2 W_{11}(i-1) + 6\,G\,A_{11}(i-1) - 3\,G\,W_{11}(i-1)$$

$$W_{22}(i) = -27\,G^2 A_{12}(i-2) + 9\,G^2 W_{12}(i-2) - 18\,G^2 A_{12}(i-1) + 9\,G^2 W_{12}(i-1) + 6\,G\,A_{12}(i-1) - 3\,G\,W_{12}(i-1)$$

$$\ldots (A9)$$

and $W_{jk}(0) = W_{jk}(1) = 0$

$$W_{11}(2) = 6G \qquad W_{12}(2) = 3G$$

$$W_{21}(2) = -27G^2 \qquad W_{22}(2) = -18G^2 + 6G$$

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SOME STATISTICAL ANALYSIS ISSUES FOR SYSTEM SIMULATION RESEARCH

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ABSTRACT

Some issues concerning system simulation research are posed and some preliminary results are given. Suggestions for further research are also given.

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1. Introduction

In this project we are mainly concerned with some issues in statistical analysis for system simulation research. We use RPV Study V data base as a working model for identifying the issues and for examining three of these. It is hoped that this effort will offer some insight into the experiment and provide some guidelines for future system simulation in general and for RPV studies in particular.

In the RPV Study V, five independent variables are used in the design matrix. They are

X_1 = telemetry time, seconds;

X_2 = command link time, seconds;

X_3 = call delay time, seconds;

X_4 = CRT update time, seconds;

X_5 = number of RPVs.

The five variables were varied in combination with each other according to a Central Composite/Fractional Factorial experimental design. This type of design allows one to investigate a large, multivariate experimental space by taking a minimum number of observations. An observation is a single execution of the RPV system simulation. Thirty-two observations (5 of these are replications) were obtained on each of four operator teams, yielding a total of 128 observations. Forty-six dependent variable measures of RPV system performance were taken.

Some detailed accounts of the experiment are given in Aume, et al. (1977).

2. Statistical Analysis

In Aume, et al. (1977), each dependent variable was treated as a univariate random variable with 32 observations and the following second order multiple regression was fitted:

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_{11} X_1^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3$$
$$+ \beta_{14} X_1 X_4 + \beta_{15} X_1 X_5 + \beta_{22} X_2^2 + \beta_{23} X_2 X_3 + \beta_{24} X_2 X_4 + \beta_{25} X_2 X_5 + \beta_{33} X_3^2$$
$$+ \beta_{34} X_3 X_4 + \beta_{35} X_3 X_5 + \beta_{44} X_4^2 + \beta_{45} X_4 X_5 + \beta_{55} X_5^2 + \epsilon$$

where ϵ is a random error and is normally distributed with mean 0 and variance σ^2, β's are unknown parameters and X's are the known independent variables. Regression equations and confidence intervals were given in the above-mentioned report for fifteen selected dependent RPV system measures when four teams are collapsed together. Some questions worth considering are:

a. Are the 32 observations (or missions) for each dependent variable really uncorrelated? If not, then weighted least squares would be more appropriate.

b. Do the four teams behave similarly? If not, the equation fitted for collapsed data may not be useful to describe performance of an individual team.

c. Are the four teams statistically independent?

d. Since there are only 32 observations, do we really need 21 terms in the equation?

e. What should be done with bad points or missing values?

f. What is the relationship between independent and dependent variables for the overall system performance?

g. Which set of independent variables contributes most to the system performance?

h. Is there any multicollinearity in the independent variables?

i. Will the ridge regression method be useful on the data set?

j. Are the dependent variables uncorrelated? If not, then multivariate analysis is in order. This will give shorter confidence intervals as correlations among different dependent variables are taken into consideration. Multivariate analysis is also capable of testing performance of several sets of dependent variables as well as pairwise comparison which is also of interest to the imagery study.

In this report we will focus exclusively on the first three issues.

2.1 Examining runs in the time sequence plot of residuals.

The purpose of the examination of runs of the time sequence plot of residuals is to detect if the randomness of the observations is valid. If not, then we can conclude that the observations are not uncorrelated and hence weighted least squares will give a better result.

For a given sequence of "+" and "-" signs, suppose there are n_1 plus signs, n_2 minus signs and u runs. Then we can use the following large sample run test. The procedure is reliable if $n_1 > 10$ and $n_2 > 0$.

Let $\mu = \frac{2n_1n_2}{n_1+n_1} - 1$

$$\sigma^2 = \frac{2n_1n_2(2n_1n_2-n_1-n_2)}{(n_1+n_2)^2(n_1+n_2-1)}$$

$$z = \frac{u-\mu+\frac{1}{2}}{\sigma}$$

TABLE 1

Residuals of the difference between ATA and ETA when fitted with second degree polynomial with five independent variables.

Team 1	*Team 2*	*Team 3*	*Team 4*	*Collapsed*
-1.91186970	1.09139735	-0.02084508	-1.47476477	-0.57901894
4.86281364	-0.00946098	-1.26382841	-1.42849311	0.54026439
-11.33011136	2.05366402	-2.54957008	-11.77656477	-5.90063561
17.71874697	1.49407235	-0.27437008	7.50176856	6.51005606
-18.72307311	-0.10463636	-1.94274735	-4.41329129	-6.29590795
19.62281364	-1.71167765	-0.27062841	6.87976856	6.63006439
11.27221023	-6.89715303	1.92686932	7.26335871	3.39130871
10.79692689	-3.50906970	0.04365265	16.20324205	5.88369205
-3.81593636	4.29714735	-0.02458674	-2.85276477	-0.59902727
4.52517197	1.58458068	-2.20543674	3.04144356	1.78645606
10.94406364	2.59493068	0.96361326	7.45550189	5.49077273
-14.91493977	-6.51613636	-1.93526402	-1.65729129	-6.25589129
11.18170530	0.90088902	1.91022159	2.96556023	4.24458106
-32.27243977	2.09708030	0.54321932	-4.50582462	-8.53447462
14.26302159	-2.99200455	5.00458523	1.00229432	4.31944432
3.42988864	0.35144735	-1.55637008	-1.46829811	0.18916439
1.76346364	1.86315568	-0.61850341	-7.31623977	-1.07703561
-31.79715644	-1.29100303	2.42643598	-13.44570795	-11.02685795
16.52346364	0.16093902	0.37469659	2.99202689	5.01276439
3.66753030	-1.34259432	-0.61476174	-5.93823977	-1.05702727
0.11341023	-2.02916970	3.11470265	16.19030871	4.34732538
-6.08528977	1.71606364	4.40535265	4.41482538	1.11272538
1.52582197	3.55719735	-1.56011174	-2.84629811	0.16915606
-5.01121970	2.96401402	0.62447992	-7.36250644	-2.19631894
-2.27715644	-4.69543636	4.41283598	7.17082538	1.15274205
-21.11363977	-2.77090303	-0.64461402	-13.43277462	-9.49049129
10.20457197	-0.74941098	-2.79935341	-1.42203144	1.30844773
34.54752159	8.14869545	-0.13881477	20.57559432	15.78324432
11.11962159	-2.61300455	0.29288523	0.86259432	2.41554432
-26.73357841	-4.13530455	-3.13801477	-3.56720568	-9.39475568
10.11782159	10.38719545	3.71948523	-5.63720568	4.64684432
-22.30917841	-3.99550455	-8.21021477	-15.99360568	-12.62715568

TABLE 2

Summary of run test.

	u	n_1	n_2	μ	σ^2	z
Team 1	21	19	13	16.4	7.2	1.9
Team 2	18	16	16	17	7.7	0.4
Team 3	17	14	18	16.8	7.5	0.3
Team 4	19	14	18	16.8	7.5	0.8
Collapsed	23	19	13	15.4	7.2	3.

Then the hypothesis of randomness is rejected at the level of significance α if

$$P(Z \leq z) < \alpha$$

where Z is a normally distributed random variable with mean 0 and variance 1. For table, see Draper and Smith (1966).

Since this study is preliminary in nature, we simply select one independent variable for illustration. The dependent variable under study is the difference between actual time of arrival (ATA) and expected time of arrival (ETA). Table 1 gives the residuals of the four teams and the collapsed data. Table 2 gives the values of u, n_1, n_2, μ, σ^2 and z. From Table 2 it is clear that at the level of significance $\alpha = 0.05$ or 0.01 the hypothesis of randomness is not rejected for any of the five cases. Thus, it seems reasonable to use unweighted least squares for this particular dependent variable.

2.2 Test of independence teams

Let $\underset{\sim}{Y}^{(j)}$ be an N×1 observed vector for the jth team with expectation

$$E\left(\underset{\sim}{Y}^{(j)}\right)_{N\times q} = \underline{\overline{X}}'\beta^{(j)}$$

where $\underline{\overline{X}}'$ is a N×q design matrix, $\beta^{(j)}$ a q×1 unknown vector, and covariance matrix

$$\mathrm{Cov}\left(\underset{\sim}{Y}^{(j)}\right) = \sigma_j^2 I$$

where σ_j^2 is an unknown scalar and I is an identity matrix for j = 1, ..., K.

In our study K = 4. But results presented in this section are valid for any positive integer K. As before, normality of observation is assumed. Putting all observations together we have the following matrix equations:

$$E(Y) = B\underline{\overline{X}}$$

and covariance matrix of the ith column of Y is

$$\Sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} & \cdots & \sigma_{1K} \\ \sigma_{21} & \sigma_{22} & \cdots & \sigma_{2K} \\ \vdots & & & \\ \sigma_{K1} & \sigma_{K2} & \cdots & \sigma_{KK} \end{pmatrix}$$

where

$$Y = \begin{pmatrix} \underset{\sim}{y}^{(1)'} \\ \vdots \\ \underset{\sim}{y}^{(K)'} \end{pmatrix}, \quad B = \begin{pmatrix} \underset{\sim}{\beta}^{(1)'} \\ \vdots \\ \underset{\sim}{\beta}^{(K)'} \end{pmatrix} \quad \text{and}$$

$$\sigma_{jj} = \sigma_j^2 \text{ for } j = 1, \ldots, K.$$

Two hypotheses of interest are

$$H_1: \ \Sigma = \begin{pmatrix} \sigma_{11} & \cdots & 0 & \cdots & 0 \\ 0 & & \sigma_{22} & & 0 \\ \vdots & & & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & \sigma_{KK} \end{pmatrix}$$

$$H_2: \ \Sigma = \sigma^2 I$$

If the hypothesis H_1 is true, then we conclude that the K teams are independent. If the hypothesis H_2 is true, then the K teams are not only independent, they are also with identical variance, i.e. $\sigma_1^2 = \cdots = \sigma_K^2 = \sigma^2$. The likehood ratio criterion for testing H_1 is

$$V_1 = \frac{|A|^{N/2}}{\prod_{j=1}^{K} A_{jj}^{N/2}}$$

where

$$A = Y[I-\underline{X}'(\underline{XX}')^{-1}\underline{X}]Y'$$

and

$$A = (A_{ij}).$$

The null hypothesis is rejected at α level if $-2\ell og_e V_1$ is greater than the upper 100α% point. For upper 5% points of the distribution of $-2\ell og_e V_1$ see Lee, Chang and Krishnaiah (1977).

The likelihood ratio criterion for testing the sphericity hypothesis H_2 is

$$V_2 = \frac{|A|}{(\text{tr } A/K)^K}$$

The null hypothesis is rejected at α level if V_2 is smaller than the lower 100α% point. For 5% and 1% points of the distribution of V_2, see Nagarsenker and Pilla (1973).

2.3 Test of homogeneity of regression curves.

The hypothesis to be tested is

$$H_3: \quad \underset{\sim}{\beta}^{(1)} = \underset{\sim}{\beta}^{(2)} = \ldots = \underset{\sim}{\beta}^{(K)}$$

If the hypothesis H_3 is true, then we have K identical regression curves and hence collapsed may be a very good way of obtaining information in this experiment. Otherwise, results obtained from collapsed data may not be very good for inference purposes for individual teams.

In order to test the hypothesis H_3 we use the likelihood ratio criterion which is

$$V_3^* = -\{n-\tfrac{1}{2}(p-q+1)\}\log_e V_3/\chi^2_{pq}(\alpha)$$

where

$$V_3 = \frac{|C(Y-\hat{B}\underline{X})(Y-\hat{B}\underline{X})'C'|}{|C(Y-\hat{B}\underline{X})(Y-\hat{B}X)'C'+C\hat{B}\underline{X}\underline{X}'\hat{B}'C'|}$$

$p = K-1$, $n = N-q$ and $\chi^2_{pq}(\alpha)$ is the upper $100\alpha\%$ point of χ^2 distribution with pq degrees of fredom. The null hypothesis H_3 is rejected at α level if $V_3^* > c$ where

$$P(V_3^* \leq c) = 1-\alpha$$

For the percentage points of the distribution of V_3^* see Krishnaiah and Lee (1979).

2.4 Concluding remarks and recommendations.

Due to limitation of computing facility and time, only very limited investigation has been done. Definitely more effort is needed to explore the issues listed in Section 2.1. It is hoped that a research proposal will be ready soon as a follow-up of this project for the AFOSR mini-grant program.

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FINAL REPORT

Effects of Hydrazine on Pregnant ICR Mice

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by

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ABSTRACT

As more women enter jobs formerly held by men there is a risk that exposure to some chemicals may cause birth defects in an unborn child. To determine the teratogenic potential of a chemical, it is frequently necessary to test the compound in more than one animal species. The objective of this project was to determine the usefulness of ICR Mice as a test species. Hydrazine was injected intraperitoneally on days 6,7,8 and 9 of gestation at concentrations of 4, 12, 20, 30 and 40 mg/kg body weight. Physiological saline was administered in the same manner to a control group. Hydrazine in concentrations up to 20 mg/kg body weight had no significant effect on the number of implantations per female, the mean number of viable fetuses per litter or the mean number of resorptions per litter. At concentrations of 30 and 40 mg/kg hydrazine was fetotoxic and 4 of 21 females died at a concentration of 40 mg/kg. As the dose was increased from 4 to 30 mg/kg there was an increasing percentage of litters with soft tissue anomalies with exencephaly and hydronephrosis produced most often. Skeletal abnormalities were produced at a higher frequency and at lower concentrations than soft tissue abnormalities. Supernumerary ribs accounted for most of these defects. Pregnant mice receiving 12 and 20 mg/kg showed a lower rate of weight gain during the injection period than those receiving saline or 4 mg/kg. After the injection period, from days 9 through 11, the mice receiving 12 and 20 mg/kg had the highest rate of gain.

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Special thanks go to Capt. William Keller whose daily help and cooperation made the project a success. The help of the laboratory technicians, Sgt. James Kroon, Sgt. Patricia Andrachek and Mr. Ken Beers was excellent and indispensable. Many interesting and helpful discussions were held with other members of the lab, and this added an extra dimension to a most enjoyable and worthwhile summer.

I. INTRODUCTION

The Aerospace Medical Research Laboratory, Toxic Hazards Division, has the responsibility for testing solvents, fuels and other chemical substances for possible hazards to Air Force personnel. One specific area of concern is the possible teratogenic effects of these chemicals. With more women entering jobs formerly held by men, there exists the possibility that exposure to certain chemicals may cause birth defects. Generally, birth defects from exposure to chemicals would occur if exposure took place during the first half of pregnancy when most women would still be working.

Teratogenic potential is determined by animal testing. One of the difficulties with animal tests is that no single species can serve as an adequate indicator for all chemicals. As a result it is frequently necessary to test the same chemical in more than one species. This project was designed to determine the usefulness of ICR mice for testing teratogenic potential. The missile propellent hydrazine was selected for testing in the mouse because some information on its activity in other species is known.

Hydrazine is a slightly basic, polar compound that is a strong reducing agent. The toxicity of hydrazine has long been established. Exposure to hydrazine can lead to skin rashes, fatty liver, blood disorders and tumor induction.[1] Less is known about the teratogenic effects of hydrazine. If embryos of the South African Clawed toad (Xenopus laevis) are exposed before neurulation, abnormal development occurs.[2] Hydrazine also causes defects in the neural tube and somites of chick embryos.[3]

Although tests in non-placental organisms may give insight into possible mechanisms that disrupt development, they fail to show effects that may result from maternal metabolism. In placental mammals the effects of hydrazine have been studied in the rat. Lee and Aleyassine report that hydrazine is fetotoxic when administered during the last half of pregnancy and Keller, et. al., also report fetotoxicity when hydrazine is administered on days 6-15 of gestation with days 7-9 being the most sensitive.[4-5]

II. OBJECTIVE

The objective of this project was to determine if the ICR strain of mice could be utilized as a test species for teratogenic testing of chemical compounds.

III. METHODS AND MATERIALS

Sexually mature ICR mice were obtained from Harlan Industries. They were housed in plastic cages on wood chip bedding and received Purina Mouse Chow and water ad libitum. The temperature of the room was maintained at 70-76^{o}F with a 12 hour light cycle. Four to five females were kept with each male. The females were checked for the presence of a vaginal plug early in the morning and again late in the afternoon. The day that a vaginal plug was found was designated as day zero of pregnancy. The pregnant mice were weighed daily.

Pregnant mice were assigned to a control group or to one of five experimental groups. All mice were injected intraperitoneally on days 6, 7, 8, and 9 of gestation. The control group received physiological saline. The experimental groups received hydrazine (Eastman, Rochester, New York) diluted with physiological saline at doses of 4, 12, 20, 30 and 40 mg/kg body weight.

On day 17 of gestation the pregnant females were killed and the fetuses removed by cesarian section. Using the methods from Olson and Back[6] and Wilson and Warkany[7], the number and position of each fetus was recorded, weighed and examined for abnormalities. Two thirds of the fetuses were preserved in Bouin's solution, sectioned with a razor blade and examined for soft tissue anomalies. One third of the fetuses were preserved in absolute ethanol, eviscerated, cleared in potassium hydroxide, stained with Alizirin Red S and examined for skeletal anomalies.

IV. RESULTS

The effects of hydrazine on the number of implantations and number of viable fetuses per litter are not apparent until the concentration exceeds 20 mg/kg body weight. Table 1. shows that the mean number of implantations per female is similar when the mice receive saline, 4, 12 and 20 mg/kg hydrazine. Since all of the 95% confidence intervals overlap there appears to be no significance difference between these means. The same is true for the means of viable fetuses per litter and resorptions per litter. At 30 and 40 mg/kg; however, hydrazine is fetotoxic at the early stages of gestation. At a concentration of 30 mg/kg only one female out of 30 judged to be pregnant produced a litter. At 40 mg/kg none of the 21 females judged to be pregnant produced a litter. Four of these 21 females died while there were no pregnant female deaths at any of the other concentrations tested.

The frequency of soft tissue abnormalities is presented in Table 2. There is an increasing frequency of soft tissue anomalies as the dose is increased. Of the litters exposed to saline, 19% had at least one soft tissue abnormality. At a dose of 4 mg/kg the percentage increases to 31, followed by 44% at 12 mg/kg, 62% at 20 mg/kg and 100% at 30 mg/kg where only 1 litter was produced. Exencephaly and hydronephrosis were the most frequently produced soft tissue anomalies. At 20 mg/kg the largest number of litters and the most fetuses were effected.

The results of the examination for skeletal abnormalities show little difference between the control and those receiving 4 mg/kg (Table 3.). However, all of the litters from females receiving 12, 20 and 30 mg/kg had skeletal malformations. By far the most prevalent abnormality was supernumerary ribs with two occurances of short ribs and one with a bipartite vertebral centrum. It appears that hydrazine produces skeletal abnormalities more frequently and at lower concentrations than soft tissue abnormalities in ICR mice.

Hydrazine also effected the weight gain of pregnant mice. During the period when injections were given, day 6 through 9, mice receiving 12 and 20 mg/kg had the slowest rate of gain (Fig 1.). From day 9 through day 13 these mice had the fastest rate of gain. In contrast, the mice receiving saline and 4 mg/kg showed essentially the same rate of gain from day 5 through day 13. On days 13 through 17 all of the mice had a similar rate of weight gain. The toxicity of hydrazine reduces the weight gain during the period of injection. When the injection period is over the mice compensate and show a more rapid rate of gain during the 4 days following injection. Those mice showing the lowest rate of weight gain during the injection period also had the highest number of anomalies in their offspring. The one litter produced from the group receiving 30 mg/kg is not graphed and no litters were produced when 40 mg/kg was used.

V. RECOMMENDATIONS

The ICR strain of mice can be used as an additional species for teratogenic testing. Although the fetuses are smaller than rat fetuses, no difficulty was encountered in making or examining razor blade sections. Clearing in potassium hydroxide and staining with Alizirin Red S works well and takes less time than a rat fetus due to the smaller size. These mice breed well in the laboratory, and no difficulties in handling were encountered.

The data presented here can be used with existing data to help assess the potential hazards of hydrazine.

Table 1.

Effect of Hydrazine on the Mean Number of Implantations, Viable Fetuses and Resorptions.

		Hydrazine		
	Saline	4 mg/kg	12 mg/kg	20 mg/kg
Number of Litters Examined	16	16	9	13
Implants/Female Means ± SE	11.44 ± 0.40	11.86 ± 0.46	12.11 ± 0.98	10.54 ± 0.83
95% Confidence Limits	10.59-12.29	10.87-12.85	9.86-14.36	8.73-12.35
Viable Fetuses per Litter Mean ± SE	10.94 ± 0.55	10.75 ± 0.60	11.67 ± 0.97	9.92 ± 0.89
95% Confidence Limits	9.76-12.12	9.47-12.03	9.43-13.91	7.99-11.85
Resorptions per Litter Mean ± SE	0.50 ± 0.26	1.13 ± 0.43	0.44 ± 0.24	0.62 ± 0.24
95% Confidence Limits	-0.05-1.05	0.22-2.04	-0.12-1.00	0.09-1.15

Table 2.

Effect of Hydrazine on the Frequency of Soft Tissue Abnormalities.

		Hydrazine			
	Saline	4 mg/kg	12 mg/kg	20 mg/kg	30 mg/kg
Number of Litters (Fetuses) Examined	16(117)	16(115)	9(73)	13(91)	1(8)
Exencephaly	1(1)	2(2)		4(4)	1(1)
Meningo-encephalocoel	1(1)				
Anopthalmia				1(1)	
Microopthalmia		1(1)		1(1)	
Hydronephrosis		1(1)	1(1)	5(7)	1(1)
Hypoplasia of Teste			1(1)		
Undescended Teste			1(1)		
Enlarged Bladder	1(1)		1(1)		
Cleft Palate				1(1)	
Percent of Litters with Anomaly	19	31	44	62	100

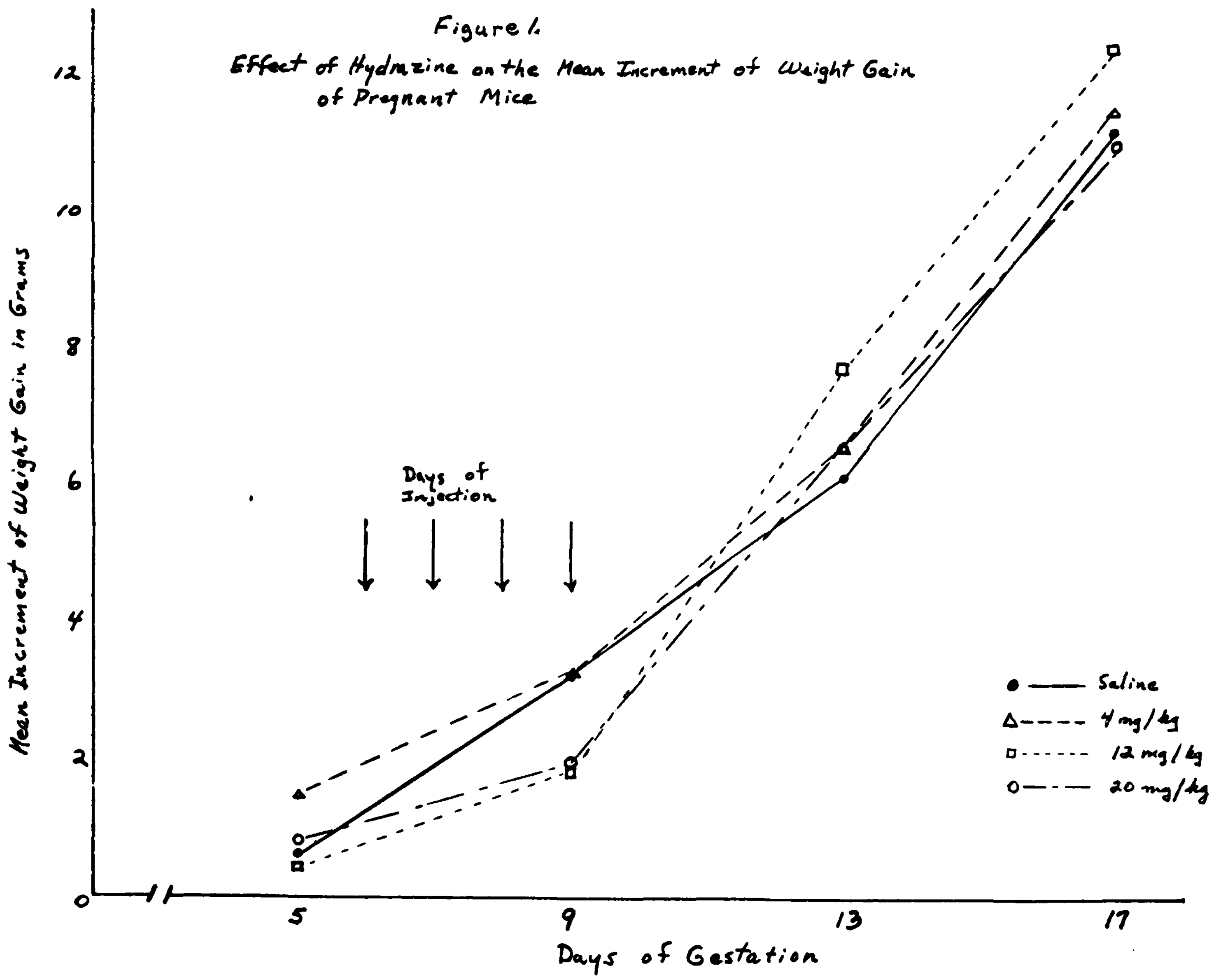
Table 3.

Effect of Hydrazine on the Frequency of Skeletal Abnormalities.

	Saline	Hydrazine 4 mg/kg	Hydrazine 12 mg/kg	Hydrazine 20 mg/kg	Hydrazine 30 mg/kg
Number of Litters (Fetuses) Examined	16(58)	16(57)	9(36)	13(38)	1(3)
Supernumerary Ribs	2(2)	1(1)	9(21)	13(31)	1(1)
Short Ribs	1(1)	1(1)			
Bipartite Centrum				1(1)	
Percent Litters with Anomaly	19	12	100	100	100

Figure 1.

Effect of Hydrazine on the Mean Increment of Weight Gain of Pregnant Mice



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FINAL REPORT

ORGANIZATIONAL ANALYSIS OF AN ACQUISITION ORGANIZATION

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ABSTRACT

An empirical study was made of the factors impacting upon the functioning of an operating unit in the government involved in carrying out the complex task of purchasing nonroutine products and services. The study was directed at the questions of (1) In what way does the technology of the job and design of the managerial system impact upon organizational processes and mission statement? (2) How have changes in workload and cuts in manpower affected the functioning of the organization and mission attainment?

The methodology was to apply Melcher's structural-process model to the analysis of the organization. Data was collected with standardized questions, interviews and with observations of the ongoing operations. The study and a more detailed supplement (2) concluded that level of efficiency and mission attainment of the operating purchasing unit was sharply impeded by a combination of structural arrangements. These included over centralization, rapid policy changes where local personnel had little opportunity to provide input on proposed changes, civil service regulations that impeded proper staffing of positions and motivation of personnel, and reductions in manpower staffing where the unit had little discretion in adapting to the manpower cuts. Proposals were made to improve the functioning of the operating purchasing unit, while retaining some of the constraints needed to achieve coordination among a wide variety of purchasing units.

ACKNOWLEDGMENTS

The Air Force Systems Command, Air Force Office of Scientific Research and the Business Research Management Center at Wright-Patterson Air Force Base have made it possible for us to intensively investigate the functioning of an operating procurement center. The personnel in the Business Research Management Center arranged for the research site, oriented us in setting up our contacts, and provided the backup operations in doing the study. Captain William Glover was an ideal representative of the Research Office; he was helpful at each stage without imposing upon us; he was available as a resource person and responded to us in providing all information and resources we needed. Col. Fortner, Col. Martin, and Major Lockwood provided the high level representation that smoothed the way for us.

Both the military and civilian supervision and operating personnel were highly cooperative at the research site. While we have not been asked to do so, we feel it better to maintain the anonymity of the research site and the personnel at the base. We want to publicly express our appreciation for the candor and open access to the entire organization. The supervision, representatives of the union, and the employees were helpful and completely cooperative to all phases of the study. We have learned a great deal and hope to share part of our understanding with them.

I. INTRODUCTION:

The level at which an organization functions determines to an important degree the efficiency and effectiveness of the government in its mission. Many of the older principles of organization that underlie present policies have been reevaluated in research studies in the last two decades. A broader understanding is developing on the way in which organizations can be designed and the way in which the supervisor can intervene in the processes to improve the functioning of the organization and carrying out of its activities. New variables have been identified as having an important impact upon the activities in organizations.

This theory is being formulated in complex contingency models. A need exists to demonstrate the way in which these complex organizational models can be used to systematically analyze and improve organizational processes. The principal attention of this study is to provide this link. A research site was sought where the operations were reasonably complex. An intensive investigation would be made of the operations and an evaluation made of the diagnostic power of the organizational model.

Several approaches may be taken to explaining and influencing the behavioral patterns in organizations. These are identified as innate personality theory, intervention theory and design theory. The three approaches emphasize different strategies in explaining and influencing the behavioral patterns.

The innate personality approach is the most intuitive and probably the most broadly believed by employees and supervisors in organizations. The approach assumes that people have certain innate characteristics and their behavior is a consequence of the qualities of individuals. Where problems exist of individual commitment, intragroup relationships or other problems, the view is that the problems are caused by the deficiencies of the people employed. Where employees are highly productive, this is a consequence of hiring people who innately possess a high degree of responsible behavior.

The intervention perspective views organizational processes as shaped by attitudes of people. Where problems occur, they are a consequence of breakdown in the processes of communication, understanding, and inadequate skills on the part of the people. Needs of people are frustrated and must be better met to solve their problems.

The design view is the least intuitive of the three approaches. Its thesis is that the context within which people operate exerts a set of pressures on people that influence and shape their behavioral patterns. Change the context within which people operate and the patterns of behavior will change.

The three approaches place different responsibilities upon the supervisor and orient him/her to take different strategies in dealing with behavioral patterns. The innate characteristics approach is simplest. If a supervisor is having difficulties with operating employees, the solution is to change the employees. If the supervisor is constrained from making personnel changes, then he can't be held responsible for the personnel problems in the unit. Employees, in turn, are likely to hold that their problems with a supervisor are due to his innate characteristics. These problems would be solved by changing the supervisor.

The view has some merit in explaining differences among individuals in a particular context. Variations in ability, personality, and other characteristics do exist. The view is limited in explanatory power, however, since it doesn't enable one to explain how changes occur in entire groups over time. While variability exists among individuals, the more striking problems are with entire groups.

The intervention perspective and design perspective provide a more persuasive explanation of factors shaping behavior. The implications of the design perspective is that the supervisor must identify the properties in the context that shape behavior and then seek to restructure or redesign the context to effect behavioral changes. If the context is largely defined by policies that are centrally determined, the approach identifies the limited influence that the supervisor can exert to shape behavioral patterns. If the context can be restructured and redesigned by the operating supervisor, then he has the technology to reshape the nature of pressures operating upon employees. The problem then is to design the context with an understanding of the way in which behavior will be positively influenced. If the context cannot be restructured, then the supervisor is largely limited to making personnel changes if this is feasible, and intervening in processes.

The intervention perspective places the burden upon the supervisor to directly intervene in the behavioral processes to solve the problems. Where conflict exists, his role is to mediate the issues; where problems of communication occur, the thrust is to mediate and clarify the issues, provide the information and correct the misunderstandings. Where poor attitudes prevail, the approach is to deal with individuals and try to elicit more positive views. The supervisor inserts himself into the interaction and transactions and mediates, facilitates and supports the processes. It requires a high level of interpersonal skill, energy, and continuous involvement. Where the supervisor is limited in dealing with the technology of the workplace, 'is or her influence is likely to rest upon these interventi. skills.

Each of these approach provides an understanding of organizational processes. This study focuses upon the design and intervention perspectives. Attention is on how well has the organization been designed and how effectively does the supervisor intervene in the processes.

OBJECTIVES OF THIS RESEARCH REPORT:

More specifically, this exploratory study focuses upon the factors impacting upon the functioning of an operating unit in the government. Two questions are addressed in the study:

1. In what way does the technology of the job and design of the management system impact upon organizational processes and mission attainment?

2. How have changes in workload and cuts in manpower affected the functioning of the organization and mission attainment.

METHODOLOGY:

The functioning of a Procurement Management (PM) organization at an Air Force installation has been studied. In addition, the engineering unit (TOE) that deals with the user and initiates a large portion of the nonroutine purchase requests was included in the study. Melcher's "organization structure-process" model was applied to identify organization processes and a set of factors affecting these processes (1, 3). The properties of the organization structure and processes have been measured in two ways. First, we used a standardized questionnaire that we devised to identify the common properties of the organizational processes, structured context, and leadership style. Second, interviews with key supervisor and operating personnel were held. Third, observations of their operations provide supplementary data on qualitative aspects of the organization.

The union that represented the employees was briefed on the study and their cooperation was elicited. Union representatives raised questions on who would be involved in the study, whether participation was voluntary, whether questionnaires could be filled out on the job, and the degree confidentiality of individual responses would be maintained. These issues were dealt with and the union cooperated on the study.

The procedure followed was to be at the site of operations for 12 weeks during the summer of 1979. On a presite visit, we identified the scope of the study, were introduced to the supervision in the PM group and were oriented on organizational changes that had taken place the last three years.

In the first six weeks of the study, we observed the operations, identified several additional properties that would be useful to measure and added these to the questionnaire. During the last six weeks of the study, we continued the monitoring of the operations and our interviews with key personnel. The questionnaire was administered during the 7th week; those absent or missed were picked up on the 9th week.

An initial analysis of the data was completed during the 9-10th weeks and initial feedback was provided during the 11th week.

Limitations of the study. The focus of the study was on the PM unit with attention given to contracting, contract administration and quality assurance. The study also included TOE of the engineering group where the focus was on its relationship with the PM unit. The study is on the problems and perspectives of PM looking at other units in the organization. A broader perspective would be to examine the functioning of the entire unit with the principal focus upon TO and the user and the interface of TO with all service units including PM as indicated in Figure 1.

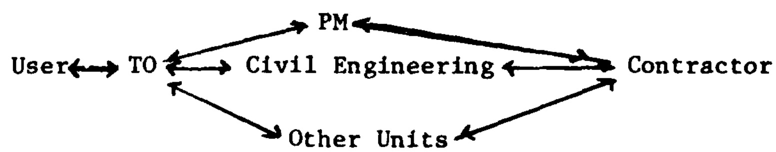

FIGURE 1 - RELATIONSHIPS IN PROCUREMENT PROCESS

It would be helpful to have a better understanding of the interfaces of the users of goods and services and identify the function performed by the government offices in mediating between the users utilizing goods and services and the contractor providing the goods and services.

A second limitation in the scope of the study is that the interviews and observations upon organizational variables have been at the operating level. The functioning of the organization has been substantially impacted by the relationship the local units have to centralized staff and line groups at higher levels and policies formulated at higher levels. The view we have taken is that of the local unit operating within these conditions, but we haven't evaluated the pressures that have elicited the organizational arrangements andunderlie the formulation of the policies.

Another consideraion in evaluating the study is that the units we have examined are at a crisis or near crisis point. A number of factors have contributed to this crisis atmosphere including rapid organizational changes that had been made during the previous three years, sharp changes in centrally formulated policies, systematic reductions in manpower with limited discretion on adapting to the changes in manpower, continued shift of manpower and instability of group composition as a result of civil service regulations on bumping and a contracting number of employees in the Air Force. Further, a pervasive pressure for higher performance combined with reduced discretion in means of achieving increased efficiency and effectiveness created a high level of frustration and anxiety on the part of employees.

These factors have created a special climate. It is our view that this was a fortuitous time for studying the organization. The personnel were outspoken; endemic problems emerged in more dramatic form and were more readily identifiable. Personnel were more attuned to organizational issues and hadn't lost their awareness of their feelings and responses to changes. Our view is that while the organization was not operating at a typical or normal level, we were able to observe better the functioning of the organization and identify the factors influencing the functioning. However, it is likely that the organization is liable to stabilize in the future and many of the problems being identified would recede in degree of importance over time.

FINDINGS:

1. Effects of Job Technology and Managerial System.

It is possible to identify a number of factors that adversely impact upon the behavioral patterns and organizational efficiency of the TO and PM units. It is useful to list these factors, identify the degree that local supervision is constrained in making changes, and specify some of the actions that could be taken to improve operations.

Work flow: Since TO and PM are service units acting as intermediaries between the contractor and the user, the units are stress points in the organization. If problems occur, they tend to assume a more intense quality at these points in the organization. Further, the stresses will be transmitted along the work flow with the greatest stress on PM. In other terms, behavioral problems are common to service organizations and any factor that impacts upon their capacity to provide high level service results in problems of intergroup relationships. Further, although the problems may be traced to the technology of job design and factors outside the control of personnel, the individuals involved will tend to be attributed with lacking competency or motivation of the people involved rather than to the constraints that limit the responsiveness of the people performing the service.

In the units studied, considerable stress and friction were observed and strained relationships expressed between TO and PM. TO personnel felt that the quality and speed of service of PM was low. The problems were posed in personal terms by attributing the problems to the weakness of leadership of the PM unit and the competency of personnel performing the contracting function.

The PM personnel, in turn, felt TO didn't make reasonable adjustments to the constraints that they were all operating under. Inadequate forward planning on the part of the user and TO transmitted unreasonable demands upon Contracting to provide service. The view was that the competency of the personnel in the TO unit was lacking.

Spatial-Physical Barriers: Spatial physical barriers between units exert a pervasive influence upon interaction, communication and working out of common problems. In the units studied several spatial physical barriers existed.

- PM and TO were physically separated. The heads of the two units were located in adjacent buildings; however, the operating personnel in TOE were located about two miles away from the PM personnel.

- The TO personnel were located in a large warehouse type building. The operating units and personnel were scattered among offices in this building.

- Contracting personnel in PM were located in adjacent offices on the same floor with few barriers among the personnel. Other units in PM were located on the same floor in adjacent offices. The military head of the PM unit and his civilian counterpart were located in two offices that faced each other with a secretary located between the two. These offices were centrally located on the same floor and readily accessible to the other offices in the PM unit.

The quality assurance group, and the operating employees in one of the two contract administration units and a technical operating unit were located about 10 miles away. In this location the units were physically dispersed among separate buildings and the personnel were dispersed among working sites in the area.

The relationship among the PM personnel closely reflected the spatial physical setting. The personnel located on the Base related well together; various spontaneous parties celebrating birthdays, and special occasions were attended by personnel from each unit. Communication patterns were open and interaction maintained on a continuous basis. The supervisor of the PM unit was highly regarded by the personnel.

In contrast, the personnel located 10 miles away were not integrated with those on the Base. They considered themselves as a separate group and interacted to a low degree with the personnel on the Base. The supervisor of two of these units maintained a working relationship with the personnel on the Base and attempted to act as a communication bridge. One supervisor was located on the Base and one at the outlying site. The major sentiment of the operating personnel in the outlying areas appeared to be critical hostility, or at best neutrality. The difficulty in the relationships was personalized in their judgement of the supervision. The head of quality assurance and his supervisor on the Base were viewed as incompetent; operating personnel couldn't see the relations improving until both were replaced. In this case, the supervisor was attempting to maintain a link with the Base office and to implement the regulations as best they could be achieved. Both attempts were viewed with hostility by many of the operating personnel.

Delegation: Degree of Centralization. The PM and TO units operate within a highly centralized organization. Further, the degree of centralization was increased under the reorganization and parallel policy changes that had taken place in the previous two years. For example, the physical space was allocated by the Base Commander so the amount of space was largely given. While shifts in the available space could be made, the formal grouping of personnel was centrally determined at the Air Force level and implemented at an intermediate level; the PM head could propose regrouping but the organization had to be consistent with Air Force regulations on the organization of a PM unit; deviations had to be approved at higher levels.

In the contracting area, a reduction in authority had occurred when the authority to issue letter contracts without review and approval of higher level personnel was reduced from \$100,000 to \$10,000. The policy to emphasize competitive bidding and the associated restrictions on maintaining sole sources resulted in limiting the authority of local operating contract officers to interpret and exercise judgements on implementing Air Force policies and regulations. The effects of these two changes in policy was to sharply reduce the area of judgement that the contract officer could exercise and limit the degree that he/she could be responsive to pressures to expedite a particular contract.

The issuing of letter contracts permitted the contract officer to short-cut the normal procedure of evaluating alternative sources and negotiating the terms of a contract. A great deal of reliance was placed on this procedure to balance out the government's interest by substituting speed and responsiveness and by drawing upon the contract officer's experience to obtain the best terms on a contract for the government. In the case of sole source, the process of issuing a competitive contract is more complex and time consuming. The emphasis tends also to shift to price being the major factor in the awarding of the contract. In the case of sole contractor, the contract officer often makes a judgement that the quality of goods, reliability of service, and a broad number of qualitative considerations provide the best transaction for the government even though the terms of the contract might not be the lowest price.

Reward System and Staffing. The combinations of a high average age of civil service personnel, high ratings with limited potential for further advancement, commitment to the Florida area, institutional reward system with little flexibility for individual recognition, and high protection individuals had in their jobs with advanced seniority meant that the supervisors had limited influence over personnel in their unit. The relatively low educational level of the personnel also meant that the personnel were unlikely to bid or bid successfully for higher level positions elsewhere.

The high level age group also meant that the working units were vulnerable to potentially rapid turnover from a combination of illness, death, or voluntary early retirement. While all indications were that employees were professionally committed in their jobs, they also had low commitment to implementing the initiatives of supervision, or directives that were coming down from higher level command.

In this context, the supervisor has little control over the work force. This appeared to be the characteristic pattern in the units studied. The supervisory actions that can be taken are limited in restructuring the situation so actions must be taken which deal with these constraints.

2. <u>Effects of Changes in Work Load and Manpower Cuts</u>

The issue that was explored was how adjustments were made by technical organization, contracting, contract administration and quality assurance. A number of adjustments can be made as work demands increase. These include queuing of the work and taking longer to perform the functions, accelerating the work pace, ranking functions and eliminating low priority activities, shifting the activities to other parties, restructuring the group to achieve higher level efficiency, and restructuring the activities so that they can be performed at a more efficient level.

These forms of adjustments permit the output to be maintained with reduced staffing and higher work loads. These are alternatives to the work not being performed as work load increases. The ability to make the various adjustments to increasing work load or reduced manpower determines the consequences for the functioning of the organization.

An understanding of the way in which adaptations have been made in this organization depends upon the type of functions performed. Since the units studied are involved in acting as intermediaries between the users and the contractors, most of the adjustments involve shifting functions to either the user or supplier. Since the functions of the governmental unit are principally planning and monitoring the implementation of the plans, rather than performing actual production activity, the activities can be sharply expanded or contracted. The consequences for the government depend on the degree the functions are marginal or critical to accomplishing the mission.

TOE is responsible for developing the specifications for the goods and services, coordinating the budgets, and working with contract administration and quality assurance to determine if the terms of the contract are fulfilled. The technical organization has adapted to the increased requirements in several ways. One has been queuing of work. The work is ranked in terms of importance and that which is most critical in schedules or other criteria is pressed. An adjustment to the longer cycle time is to press the user to plan further ahead and initiate requests at an earlier stage to provide a longer time buffer from when the material is requested to when it is to be used. Another adjustment is to perform a number of activities in parallel rather than in sequence. While this increases the risk to the government since it requires an assumption that each step will be performed with satisfactory standards, it reduces the time to perform the functions.

The adjustment that has the broadest implications for the government is to shift the function of working up the technical specifications to the user or the potential contractor with little or no review by the governmental representatives. A working relationship typically exists where the specialists employed by the government rely upon the specialized competence of the user and/or the contractor. Where the government specialists are performing a key function, they make an independent assessment of the technical specifications of the user or potential contractor. Requirements may be incorporated that are unnecessary or too costly for the benefits of the government. For example, the user may be comfortable with existing suppliers of equipment and seek to maintain the continuity of that relationship. It may be that equivalent or superior supplies are available from other sources at a lower price. The role of the governmental technician would be to pose the requirements broadly enough so that competitive proposals could be obtained.

TOE can also press Contracting to expedite the entire process of procurement by obtaining exceptions to general rules. It may be a general rule that contracts above $100,000 are to be competitively bid, but for a particular user such as a foreign purchaser the rule may be waived so that the contract process can be expedited.

Where the usual processes of exerting pressure on purchasing isn't effective, the most drastic approach is to sidestep the governmental interface and have the function performed by an outside contractor. Thus, rather than submitting the item to purchasing to obtain the goods or services, the contracting function is shifted to an outside organization. The outside organization isn't restricted by the rules and regulations of the government so is in a position to accelerate the entire process.

As the process of generating the technical specifications has become more complex and lengthy, Technical has used each of these methods to continue processing the work flowing into TO. These processes are likely to continue as additional pressures are placed upon the unit by increases in work load or reductions in personnel.

Contracting also can adapt to increasing work load in similar ways. The contracting officer is the formal agent for developing a contract between the government and the supplier using the data provided by the Technical organization working in conjunction with the user and other sources. The contractor must determine the type of contract that would serve the government's interest the best--sole source, competitive, or some variation, incentive provisions, penalties for non-performance, quality assurance provisions to include in the contract, payment provisions and other legal protections for the contractor and the government. A complex set of choices are available to the contract officer and he may independently evaluate the recommendations of technical organization, or uncritically accept their recommendations.

As the complexity of purchasing increases, purchasing exerts pressure upon the user and technical to provide greater time buffers such as longer forward planning. Contracting also exerts pressure upon the supplier-particularly in the case of continuing sole source suppliers-to assume greater risks in the contracting relationship.

In effect, the supplier may be asked to proceed on the basis that a contract will be negotiated and to do its forward planning before a formal contractual commitment is made.

Contracting also can make temporary adjustments to increased demands by "storming" behavior. Personnel can be worked overtime during high demand periods and leave provided during low demand periods. Work orders can be queued and those lower on the queue completed as the work load ebbs off. Requirements can be ordered in importance and those of lesser importance given pro forma attention.

Policy directives that entail considerable extra work can be tested and exceptions to the directives developed. For instance, in the case of the requirements for competitive contracts, the conditions when the policy must be implemented can be clarified and when deviations from the policy will be accepted. In the case studied, where users were faced with increased lengthy requirements, both those staff personnel at the headquarters level and those at the operating level were pressing for these forms of policy clarifications and simplifications.

The time spent for documenting the steps tends to be reduced. Reporting requirements are abridged and higher risks are assumed by operating personnel on violations of procedures. Informal understandings and exchanges are developed between lower level operating personnel and higher level personnel charged with enforcing the policies.

The combinations of mechanization thru the use of word processors and thru specialization of functions provide a basis for improving the efficiency of contracting units. Extensive uses of word processors provide the simplest way of increasing the efficiency of more routine functions of contracting. The group was organized into contract teams with each team specializing to some degree. The potential for increased specialization would be possible with a larger group.

An announcement was made late in the study o a reorganization that would combine Base Purchasing with Contracting. This would provide an opportunity for increasing considerably specialization and lend itself to greater use of word processors in the operations. Since most contractshave a great number of common properties, the word processor permits minor variations to be made and the common provisions of the contract rapidly produced.

Quality Assurance also had the means to adapt to changes in work load and man power reductions. The quality assurance group is centrally concerned with monitoring the extent that the contractor was implementing the program prescribed in the contract. The quality assurance personnel have a set of mandatory checks to make some which must be performed visually on the site and some of which can be performed by evaluating the computer data or other records. As any monitoring function, it can be performed pro formally or closely adhered to.

One method of adapting to increased work load is to rely upon the contractor to a high degree to perform the tests without close checking. In this case the government employee must certify the contractor as meeting the requirements without independently assessing this fact. It shifts greater risk to the government since the contractor's responsibility is fulfilled once the contract requirements are certified as met.

Another method of dealing with increased work load is to press for greater degree of decentralization so that local conditions can be better adapted to. Or the unit can press headquarters for changes in policy to reduce mandatory checks to only ones that are viewed as critical to local personnel. Or the local unit may press for changes in the type of tests thatare to be made such as for a single observer rather than two or three observers; or rely upon computer generated data rather than visual data.

Adjustments can be made to short term increases in work load by shifting personnel to overtime during high demand periods and providing leave time during low demand periods. Queuing procedures can also be used and pro forma attention given to tests and activities of marginal value and by shifting time and attention to steps considered of central importance. Random tests may be made rather than preprogramed tests.

The group efficiency can be increased by personnel upgrading, specialization, and increased use of trainees. As the work load increases, close scheduling is necessary since the usual buffers are reduced. The system is more vulnerable to unanticipated absences, fluctuations in work load and unanticipated problems. The unit becomes more dependent upon drawing upon personnel outside the unit from central headquarters or other sources for temporary personnel.

In this unit, attention was being given to systematically addressesing these problems. Each of these processes of adapting to increased work load and reduced man power were being used. These adjustments, however, were associated with high stress within the group, dissatisfaction with the supervisor as he pressed the adjustments, and intergroup conflict with personnel on the Base. The actions that would be most helpful such as greater degree of local discretion to devise an appropriate quality assurance program was most difficult to effect.

In Contract Administration, various adjustments also were possible under varying work load. In this area, the adjustments were similar to a quality assurance. There is greater potential for adjustments in this area without substantial down grading of the function being performed. Where contract administration was involved in negotiating additional provisions of the contract, they had the same opportunities as Technical and Contracting to shift the functions to the user. The monitoring function and negotiation of price adjustments on open ended provisions can be performed with a good data base where information has been systematically collected, or reliance is upon data generated by the contractor. The unit was pressed to rely to a great degree upon data acquired by the contractor.

Short term adjustment to work load can be accomplished by shifting personnel from low level periods to high level periods. Longer term adjustments are effected by reviewing what functions of contract administration are critical and concentrating on these features and giving pro forma or random checks on other features of the contract. These adjustments were being made with the effect of reducing the costs of contract administration and increasing the risk to the government.

RECOMMENDATIONS

Expanded Study of Operations. Expanded studies are required to obtain a more complete understanding of the effects of present organizational design, centrally determined policy directives, and restrictions of and protections of the Civil Service System regulations particularly as they relate to staffing and bumping. Comparative studies are needed to contrast the way in which these factors affect operations where the units are faced with different conditions.

Studies with an expanded focus on all PM and TO units as they interface with both the user and contractor are needed particularly to assess the implications of reducing levels of manpower and increasing the work load on units. It is clear that one of the adjustments being made is to shift functions to the user and contractors as a result of increased work pressures on the governmental units. A close assessment is needed to evaluate to what extent short term costs savings are being achieved by long term increased risks and greater costs to the government.

Increasing the Discretion of Local Units. The Technical and Purchasing units are operating under severe constraints from policies issued by higher level administrative units. While there are obviously great pressures upon higher level units to adopt uniform policies on purchasing across all units in the Air Force, the means of achieving uniformity and co-ordination is highly destructive of efficiency and effectiveness of the operating units. Conflicts among groups are built in the system by these centralized policies that make it difficult for even dedicated professionals to do their jobs. An increasing amount of time is involved in working up technical specifications, setting in motion the process of purchasing the products or services, and obtaining the purchases. In other terms, the user is taking longer to obtain the supplies and services that are needed to carry out its responsibilities.

The solving of the problems involves several actions: The higher level organization should rely upon ends that it is trying to effect rather than the means to the ends in establishing policy constraints for the operating units. For example, a policy that was being strongly pressed would reduce sole source contracting and increase competitive bidding on contracts. The policy was being implemented by setting in motion a complex review and justification procedure for all sole source contracts. Contracts above various dollar levels had to be reviewed and approved by intermediate or highest level administrative offices. The financial committments of funds was constrained by controller policies and had to be reviewed by higher level officials. Each of these steps had to be done largely in sequence rather than parallel so extensive time was built in the system to determine if policies were being implemented.

If, on the other hand, a more flexible policy would be to established standards that required increasing percentage of contracts to be competively awarded in the next five years, the operating units could be given the discretion on how these standards were to be met. This would place the judgements where the greatest information is available and eliminate the time consuming review procedures. The operating units at the Base are not in a position to implement changes in procedure, but they can propose the procedures to higher level administrative personnel along with a clear statement of the problems of present methods.

Similarly, the interfacing of technical requirements, budgetary requirements and purchase requirements can be at either the Base level or at higher levels. At present, these policies are separately formulated at high administrative levels; the Commander of TO, PM and Accounting units at the Base have limited discretion to coordinate and reconcile differences among these units. Decisions must be continually shifted up to higher levels in the organization. Effecting changes in this structure is even more difficult. Again, though, the focus should be upon the ends that the Air Force is trying to achieve rather than on the means of achieving these ends in the formulation of policies that restrict the discretion of the operating commander of these units.

The operating units have limited ability to make adjustments in these structural arrangements. Again, attention should be given to proposing increased delegation by focusing upon ends rather than means while highlighting the problems under the present restrictions.

Spatial Physical Arrangements in the PM Group. The spatial physical dispersion among work sites will impact upon relationships within groups and between groups. This fact requires that spatial physical arrangements be established so that individuals and groups are physically located together who require an ongoing work relationship. In this organization, two basic activities are carried on: Those relating to the range contract and those relating to the space and missile contracts. The groups should be physically arranged so that the personnel are broken into two project groups to the extent that this is physically possible. The nature of the functions of these two projects require substantially different ways of approaching the work. Essentially, this means that all, or most of the personnel involved with the space and missile contracting would be located at the outlying site; those involved with the range contract would be located on the Base. In this case, changes can be implemented that would be helpful in supporting group relationships that are important in carrying out the job.

The formal grouping of units in departments is an area covered by Air Force Regulations and must be approved by higher level administrators; even at higher levels, officers are constrained by policy directives on the way in which a PM unit is to be formally orgainzed. It would be useful to organize these groups dealing with the range and space and missile business. During the study, a proposal along these lines was made by the administrator of the PM unit to higher level authorities. The proposal was rejected and further changes in organization were being made to emphasize functional specialization.

While these changes may be proposed again in the future, it is evident little change can be made until an evaluation is made at higher level administration in the Air Force of the consequences of requiring the same administrative structure on all units. The formal grouping of personnel along functional lines and physical grouping along project lines would create some problems for the supervisors of the units. It would probably require that a senior person be informally regarded as head of each specialized unit at the outlying base and at the Base. The formal supervisor would work with these operating heads in coordinating the functions where necessary. Similarly, one of the senior unit supervisors or other senior official would need to be designated as informal heads of each of the project groups. This places a high reliance upon an effective functioning informal organization, but it is a reasonable accommodation to a situation that is poorly formally structured.

Reward System and Staffing. The supervisors are operating within the constraints of the Civil Service System and its policies on salaries, merit increases, bidding rights on jobs, bumping rights with reductions in personnel, and central determination of qualifications of personnel. The effects of this set of regulations is to place a high emphasis upon the protection of individuals who have greatest seniority in their claim to a job in the organization and promotion to positions in the organization. However, it provides the individual low protection in his/her claim to the present job, or to the present rank. The regulations place low priority upon supervisor control of staffing and **motivating** of present personnel to high levels of effort. The total system sharply impedes the building of an efficient unit.

A broad number of changes in the Civil Service System is needed to provide a better balance of protection for the senior employee and the provision for controls that would enable the supervisor to carry out assigned responsibilities. These include but are not limited to a sharply reduced bumping potential when jobs are downgraded or phased out, increased discretion of the supervisor in awarding merit increases, increased authority of the supervisor to promote outstanding personnel in his unit, and greater authority to select personnel to fill vacant positions. Changes in these regulations, however, are unlikely to be made since these regulations are codified by Congress and Civil Service Commission.

Feasible actions are limited to operating within Civil Service regulations. One set of actions deals with establishing a skill hierarchy within each area and bringing trainees into these positions. A systematic program of regrading positions so that a hierarchy of grades exist within each unit would create the potential for exerting greater influence over employees. As positions were vacated by retirements, transfers or other reasons, attention should be given to establishing a hierarchy of grades within the groups. Second, all units should be involved in bringing trainees into the lower level positions. This would provide a basis for bringing in personnel with skills that are more likely to be relevant to the complex environment of the 1980's and 1990's with the revolutions in computer technology, word processors, and other technical changes in jobs. Perhaps as important, a basis is established for using the reward system to motivate and influence behavior. Trainees and those employees in midcareer are more likely to be responsive to initiatives of supervision and to changes in organization arrangements or policy revisions.

Intervention Methods.

A second approach to influencing the organization process is for the supervisor to actively intervene in the processes, expediting communication exchanges, reconciling conflicts, praising outstanding performance and buffer destructive pressures on the units. The head of the PM unit was especially skilled at intervention and made an extremely difficult situation workable for most of the employees. He set a tenor and tone for the other supervisors that was constructive and positive as they dealt with onerous constraints and high pressures for performance from higher level administrators and other parallel units.

A few additional areas of intervention would be helpful in facilitating the organizational processes. While a stress relationship is always likely to exist in the independent work flow with the centralized constraints between TOE and PM, personnel in neither unit had much appreciation for the problems of the other unit. A monthly or bimonthly meeting of supervisors and key personnel with an agreed upon agenda would be helpful. Such a regularly scheduled session would permit recurring problems to be highlighted, discussion of constraints for solving the problems and proposals for dealing with the problems jointly agreed upon.

Similarly, the spatial physical distance between the Base office and the outlying site at the space and missile program create problems of communication and intergroup relationships. The administrator could improve the relationships by a couple of symbolic and expediting acts.

Staff meetings were regularly scheduled at the Base Headquarters. These staff meetings could be scheduled alternatively at the Base and at the outlying site. This would symbolize the equal importance of the personnel and activities at the Base. Since the Administrater was particularly personable, it would provide an opportunity to interact with the employees at the outlying site and communicate his interest and attention to their activities.

Second, problem sessions with unit supervisors and key operating personnel could be regularly scheduled at the outlying site. If an agenda was agreed upon ahead of time and input solicited on problems and ideas for solving them, it would provide an opportunity for the direct expression of strong feelings on part of many of the personnel.

The staff meetings could serve this function, but the tradition of only supervisors actively participating would need to be modified.

The combinations of structural changes that are feasible and intervention methods would be helpful in solving some of the problems. However, the organization is operating under conditions of a classic level of over centralization, declining levels of supportive resources, and increasing pressures for performance. Actions are taken centrally with little input or understanding and/or concern for functioning of the units. It is remarkable that the level of professionalism that was observed is maintained under these conditions.

Broad changes are required to make striking improvements in the operations. Broad scale studies commissioned at the Air Force top levels that highlight the problems and provide feasible alternatives would likely create the documentation for effecting broad scale changes. Until then, a great deal of emphasis will have to be placed on how the supervisors can operate effectively in a poorly designed situation.

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FINAL REPORT

ORGANIZATIONAL ANALYSIS OF AN ACQUISITION ORGANIZATION

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ORGANIZATIONAL ANALYSIS OF AN ACQUISITION ORGANIZATION

by

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and

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ABSTRACT

An empirical study was made of the factors impacting upon the functioning of an operating unit in the government involved in carrying out the complex task of purchasing nonroutine products and services. The study was directed at the questions of (1) In what way does the technology of the job and design of the managerial system impact upon organizational processes and mission statement? (2) How have changes in workload and cuts in manpower affected the functioning of the organization and mission attainment?

The methodology was to apply Melcher's structural-process model to the analysis of the organization. Data was collected with standardized questions, interviews and with observations of the ongoing operations. The study and a more detailed supplement (2) concluded that level of efficiency and mission attainment of the operating purchasing unit was sharply impeded by a combination of structural arrangements. These included over centralization, rapid policy changes where local personnel had little opportunity to provide input on proposed changes, civil service regulations that impeded proper staffing of positions and motivation of personnel, and reductions in manpower staffing where the unit had little discretion in adapting to the manpower cuts. Proposals were made to improve the functioning of the operating purchasing unit, while retaining some of the constraints needed to achieve coordination among a wide variety of purchasing units.

ACKNOWLEDGMENTS

The Air Force Systems Command, Air Force Office of Scientific Research and the Business Research Management Center at Wright-Patterson Air Force Base have made it possible for us to intensively investigate the functioning of an operating procurement center. The personnel in the Business Research Management Center arranged for the research site, oriented us in setting up our contacts, and provided the backup operations in doing the study. Captain William Glover was an ideal representative of the Research Office; he was helpful at each stage without imposing upon us; he was available as a resource person and responded to us in providing all information and resources we needed. Col. Fortner, Col. Martin, and Major Lockwood provided the high level representation that smoothed the way for us.

Both the military and civilian supervision and operating personnel were highly cooperative at the research site. While we have not been asked to do so, we feel it better to maintain the anonymity of the research site and the personnel at the base. We want to publicly express our appreciation for the candor and open access to the entire organization. The supervision, representatives of the union, and the employees were helpful and completely cooperative to all phases of the study. We have learned a great deal and hope share part of our understanding with them.

I. INTRODUCTION:

The level at which an organization functions determines to an important degree the efficiency and effectiveness of the government in its mission. Many of the older principles of organization that underlie present policies have been reevaluated in research studies in the last two decades. A broader understanding is developing on the way in which organizations can be designed and the way in which the supervisor can intervene in the processes to improve the functioning of the organization and carrying out of its activities. New variables have been identified as having an important impact upon the activities in organizations.

This theory is being formulated in complex contingency models. A need exists to demonstrate the way in which these complex organizational models can be used to systematically analyze and improve organizational processes. The principal attention of this study is to provide this link. A research site was sought where the operations were reasonably complex. An intensive investigation would be made of the operations and an evaluation made of the diagnostic power of the organizational model.

Several approaches may be taken to explaining and influencing the behavioral patterns in organizations. These are identified as innate personality theory, intervention theory and design theory. The three approaches emphasize different strategies in explaining and influencing the behavioral patterns.

The innate personality approach is the most intuitive and probably the most broadly believed by employees and supervisors in organizations. The approach assumes that people have certain innate characteristics and their behavior is a consequence of the qualities of individuals. Where problems exist of individual commitment, intragroup relationships or other problems, the view is that the problems are caused by the deficiencies of the people employed. Where employees are highly productive, this is a consequence of hiring people who innately possess a high degree of responsible behavior.

The intervention perspective views organizational processes as shaped by attitudes of people. Where problems occur, they are a consequence of breakdown in the processes of communication, understanding, and inadequate skills on the part of the people. Needs of people are frustrated and must be better met to solve their problems.

The design view is the least intuitive of the three approaches. Its thesis is that the context within which people operate exerts a set of pressures on people that influence and shape their behavioral patterns. Change the context within which people operate and the patterns of behavior will change.

The three approaches place different responsibilities upon the supervisor and orient him/her to take different strategies in dealing with behavioral patterns. The innate characteristics approach is simplest. If a supervisor is having difficulties with operating employees, the solution is to change the employees. If the supervisor is constrained from making personnel changes, then he can't be held responsible for the personnel problems in the unit. Employees, in turn, are likely to hold that their problems with a supervisor are due to his innate characteristics. These problems would be solved by changing the supervisor.

The view has some merit in explaining differences among individuals in a particular context. Variations in ability, personality, and other characteristics do exist. The view is limited in explanatory power, however, since it doesn't enable one to explain how changes occur in entire groups over time. While variability exists among individuals, the more striking problems are with entire groups.

The intervention perspective and design perspective provide a more persuasive explanation of factors shaping behavior. The implications of the design perspective is that the supervisor must identify the properties in the context that shape behavior and then seek to restructure or redesign the context to effect behavioral changes. If the context is largely defined by policies that are centrally determined, the approach identifies the limited influence that the supervisor can exert to shape behavioral patterns. If the context can be restructured and redesigned by the operating supervisor, then he has the technology to reshape the nature of pressures operating upon employees. The problem then is to design the context with an understanding of the way in which behavior will be positively influenced. If the context cannot be restructured, then the supervisor is largely limited to making personnel changes if this is feasible, and intervening in processes.

The intervention perspective places the burden upon the supervisor to directly intervene in the behavioral processes to solve the problems. Where conflict exists, his role is to mediate the issues; where problems of communication occur, the thrust is to mediate and clarify the issues, provide the information and correct the misunderstandings. Where poor attitudes prevail, the approach is to deal with individuals and try to elicit more positive views. The supervisor inserts himself into the interaction and transactions and mediates, facilitates and supports the processes. It requires a high level of interpersonal skill, energy, and continuous involvement. Where the supervisor is limited in dealing with the technology of the workplace, his or her influence is likely to rest upon these intervention skills.

Each of these approaches provides an understanding of organizational processes. This study focuses upon the design and intervention perspectives. Attention is on how well has the organization been designed and how effectively does the supervisor intervene in the processes.

OBJECTIVES OF THIS RESEARCH REPORT:

More specifically, this exploratory study focuses upon the factors impacting upon the functioning of an operating unit in the government. Two questions are addressed in the study:

1. In what way does the technology of the job and design of the management system impact upon organizational processes and mission attainment?

2. How have changes in workload and cuts in manpower affected the functioning of the organization and mission attainment.

METHODOLOGY:

The functioning of a Procurement Management (PM) organization at an Air Force installation has been studied. In addition, the engineering unit (TOE) that deals with the user and initiates a large portion of the nonroutine purchase requests was included in the study. Melcher's "organization structure-process" model was applied to identify organization processes and a set of factors affecting these processes (1, 3). The properties of the organization structure and processes have been measured in two ways. First, we used a standardized questionnaire that we devised to identify the common properties of the organizational processes, structured context, and leadership style. Second, interviews with key supervisor and operating personnel were held. Third, observations of their operations provide supplementary data on qualitative aspects of the organization.

The union that represented the employees was briefed on the study and their cooperation was elicited. Union representatives raised questions on who would be involved in the study, whether participation was voluntary, whether questionnaires could be filled out on the job, and the degree confidentiality of individual responses would be maintained. These issues were dealt with and the union cooperated on the study.

The procedure followed was to be at the site of operations for 12 weeks during the summer of 1979. On a presite visit, we identified the scope of the study, were introduced to the supervision in the PM group and were oriented on organizational changes that had taken place the last three years.

In the first six weeks of the study, we observed the operations, identified several additional properties that would be useful to measure and added these to the questionnaire. During the last six weeks of the study, we continued the monitoring of the operations and our interviews with key personnel. The questionnaire was administered during the 7th week; those absent or missed were picked up on the 9th week.

An initial analysis of the data was completed during the 9-10th weeks and initial feedback was provided during the 11th week.

Limitations of the study. The focus of the study was on the PM unit with attention given to contracting, contract administration and quality assurance. The study also included TOE of the engineering group where the focus was on its relationship with the PM unit. The study is on the problems and perspectives of PM looking at other units in the organization. A broader perspective would be to examine the functioning of the entire unit with the principal focus upon TO and the user and the interface of TO with all service units including PM as indicated in Figure 1.

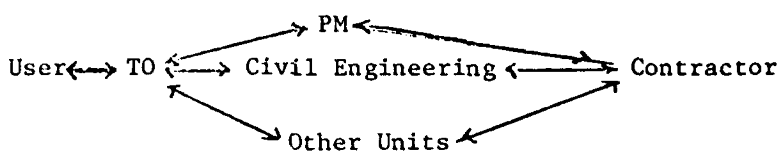

FIGURE 1 - RELATIONSHIPS IN PROCUREMENT PROCESS

It would be helpful to have a better understanding of the interfaces of the users of goods and services and identify the function performed by the government offices in mediating between the users utilizing goods and services and the contractor providing the goods and services.

A second limitation in the scope of the study is that the interviews and observations upon organizational variables have been at the operating level. The functioning of the organization has been substantially impacted by the relationship the local units have to centralized staff and line groups at higher levels and policies formulated at higher levels. The view we have taken is that of the local unit operating within these conditions, but we haven't evaluated the pressures that have elicited the organizational arrangements andunderlie the formulation of the policies.

Another consideraion in evaluating the study is that the units we have examined are at a crisis or near crisis point. A number of factors have contributed to this crisis atmosphere including rapid orgE izational changes that had been made during the previous three years, sharp changes in centrally formulated policies, systematic reductions in manpower with limited discretion on adapting to the changes in manpower, continued shift of manpower and instability of group composition as a result of civil service regulations on bumping and a contracting number of employees in the Air Force. Further, a pervasive pressure for higher performance combined with reduced discretion in means of achieving increased efficiency and effectiveness created a high level of frustration and anxiety on the part of employees.

These factors have created a special climate. It is our view that this was a fortuitous time for studying the orga ation. The personnel were outspoken; endemic problems emerged in more dramatic form and were more readily identifiable. Personnel were more attuned to organizational issues and hadn't lost their awareness of their feelings and responses to changes. Our view is that while the organization was not operating at a typical or normal level, we were able to observe better the functioning of the organization and identify the factors influencing the functioning. However, it is likely that the organization is liable to stabilize in the future and many of the problems being identified would recede in degree of importance over time.

FINDINGS:

1. Effects of Job Technology and Managerial System.

It is possible to identify a number of factors that adversely impact upon the behavioral patterns and organizational efficiency of the TO and PM units. It is useful to list these factors, identify the degree that local supervision is constrained in making changes, and specify some of the actions that could be taken to improve operations.

Work flow: Since TO and PM are service units acting as intermediaries between the contractor and the user, the units are stress points in the organization. If problems occur, they tend to assume a more intense quality at these points in the organization. Further, the stresses will be transmitted along the work flow with the greatest stress on PM. In other terms, behavioral problems are common to service organizations and any factor that impacts upon their capacity to provide high level service results in problems of intergroup relationships. Further, although the problems may be traced to the technology of job design and factors outside the control of personnel, the individuals involved will tend to be attributed with lacking competency or motivation of the people involved rather than to the constraints that limit the responsiveness of the people performing the service.

In the units studied, considerable stress and friction were observed and strained relationships expressed between TO and PM. TO personnel felt that the quality and speed of service of PM was low. The problems were posed in personal terms by attributing the problems to the weakness of leadership of the PM unit and the competency of personnel performing the contracting function.

The PM personnel, in turn, felt TO didn't make reasonable adjustments to the constraints that they were all operating under. Inadequate forward planning on the part of the user and TO transmitted unreasonable demands upon Contracting to provide service. The view was that the competency of the personnel in the TO unit was lacking.

Spatial-Physical Barriers: Spatial physical barriers between units exert a pervasive influence upon interaction, communication and working out of common problems. In the units studied several spatial physical barriers existed.

- PM and TO were physically separated. The heads of the two units were located in adjacent buildings; however, the operating personnel in TOE were located about two miles away from the PM personnel.

- The TO personnel were located in a large warehouse type building. The operating units and personnel were scattered among offices in this building.

- Contracting personnel in PM were located in adjacent offices on the same floor with few barriers among the personnel. Other units in PM were located on the same floor in adjacent offices. The military head of the PM unit and his civilian counterpart were located in two offices that faced each other with a secretary located between the two. These offices were centrally located on the same floor and readily accessible to the other offices in the PM unit.

The quality assurance group, and the operating employees in one of the two contract administration units and a technical operating unit were located about 10 miles away. In this location the units were physically dispersed among separate buildings and the personnel were dispersed among working sites in the area.

The relationship among the PM personnel closely reflected the spatial physical setting. The personnel located on the Base related well together; various spontaneous parties celebrating birthdays, and special occasions were attended by personnel from each unit. Communication patterns were open and interaction maintained on a continuous basis. The supervisor of the PM unit was highly regarded by the personnel.

In contrast, the personnel located 10 miles away were not integrated with those on the Base. They considered themselves as a separate group and interacted to a low degree with the personnel on the Base. The supervisor of two of these units maintained a working relationship with the personnel on the Base and attempted to act as a communication bridge. One supervisor was located on the Base and one at the outlying site. The major sentiment of the operating personnel in the outlying areas appeared to be critical hostility, or at best neutrality. The difficulty in the relationships was personalized in their judgement of the supervision. The head of quality assurance and his supervisor on the Base were viewed as incompetent; operating personnel couldn't see the relations improving until both were replaced. In this case, the supervisor was attempting to maintain a link with the Base office and to implement the regulations as best they could be achieved. Both attempts were viewed with hostility by many of the operating personnel.

Delegation: Degree of Centralization. The PM and TO units operate within a highly centralized organization. Further, the degree of centralization was increased under the reorganization and parallel policy changes that had taken place in the previous two years. For example, the physical space was allocated by the Base Commander so the amount of space was largely given. While shifts in the available space could be made, the formal grouping of personnel was centrally determined at the Air Force level and implemented at an intermediate level; the PM head could propose regrouping but the organization had to be consistent with Air Force regulations on the organization of a PM unit; deviations had to be approved at higher levels.

In the contracting area, a reduction in authority had occurred when the authority to issue letter contracts without review and approval of higher level personnel was reduced from $100,000 to $10,000. The policy to emphasize competitive bidding and the associated restrictions on maintaining sole sources resulted in limiting the authority of local operating contract officers to interpret and exercise judgements on implementing Air Force policies and regulations. The effects of these two changes in policy was to sharply reduce the area of judgement that the contract officer could exercise and limit the degree that he/she could be responsive to pressures to expedite a particular contract.

The issuing of letter contracts permitted the contract officer to short-cut the normal procedure of evaluating alternative sources and negotiating the terms of a contract. A great deal of reliance was placed on this procedure to balance out the government's interest by substituting speed and responsiveness and by drawing upon the contract officer's experience to obtain the best terms on a contract for the government. In the case of sole source, the process of issuing a competitive contract is more complex and time consuming. The emphasis tends also to shift to price being the major factor in the awarding of the contract. In the case of sole contractor, the contract officer often makes a judgement that the quality of goods, reliability of service, and a broad number of qualitative considerations provide the best transaction for the government even though the terms of the contract might not be the lowest price.

Reward System and Staffing. The combinations of a high average age of civil service personnel, high ratings with limited potential for further advancement, commitment to the Florida area, institutional reward system with little flexibility for individual recognition, and high protection individuals had in their jobs with advanced seniority meant that the supervisors had limited influence over personnel in their unit. The relatively low educational level of the personnel also meant that the personnel were unlikely to bid or bid successfully for higher level positions elsewhere.

The high level age group also meant that the working units were vulnerable to potentially rapid turnover from a combination of illness, death, or voluntary early retirement. While all indications were that employees were professionally committed in their jobs, they also had low commitment to implementing the initiatives of supervision, or directives that were coming down from higher level command.

In this context, the supervisor has little control over the work force. This appeared to be the characteristic pattern in the units studied. The supervisory actions that can be taken are limited in restructuring the situation so actions must be taken which deal with these constraints.

2. Effects of Changes in Work Load and Manpower Cuts

The issue that was explored was how adjustments were made by technical organization, contracting, contract administration and quality assurance. A number of adjustments can be made as work demands increase. These include queuing of the work and taking longer to perform the functions, accelerating the work pace, ranking functions and eliminating low priority activities, shifting the activities to other parties, restructuring the group to achieve higher level efficiency, and restructuring the activities so that they can be performed at a more efficient level.

These forms of adjustments permit the output to be maintained with reduced staffing and higher work loads. These are alternatives to the work not being performed as work load increases. The ability to make the various adjustments to increasing work load or reduced manpower determines the consequences for the functioning of the organization.

An understanding of the way in which adaptations have been made in this organization depends upon the type of functions performed. Since the units studied are involved in acting as intermediaries between the users and the contractors, most of the adjustments involve shifting functions to either the user or supplier. Since the functions of the governmental unit are principally planning and monitoring the implementation of the plans, rather than performing actual production activity, the activities can be sharply expanded or contracted. The consequences for the government depend on the degree the functions are marginal or critical to accomplishing the mission.

TOE is responsible for developing the specifications for the goods and services, coordinating the budgets, and working with contract administration and quality assurance to determine if the terms of the contract are fulfilled. The technical organization has adapted to the increased requirements in several ways. One has been queuing of work. The work is ranked in terms of importance and that which is most critical in schedules or other criteria is pressed. An adjustment to the longer cycle time is to press the user to plan further ahead and initiate requests at an earlier stage to provide a longer time buffer from when the material is requested to when it is to be used. Another adjustment is to perform a number of activities in parallel rather than in sequence. While this increases the risk to the government since it requires an assumption that each step will be performed with satisfactory standards, it reduces the time to perform the functions.

The adjustment that has the broadest implications for the government is to shift the function of working up the technical specifications to the user or the potential contractor with little or no review by the governmental representatives. A working relationship typically exists where the specialists employed by the government rely upon the specialized competence of the user and/or the contractor. Where the government specialists are performing a key function, they make an independent assessment of the technical specifications of the user or potential contractor. Requirements may be incorporated that are unnecessary or too costly for the benefits of the government. For example, the user may be comfortable with existing suppliers of equipment and seek to maintain the continuity of that relationship. It may be that equivalent or superior supplies are available from other sources at a lower price. The role of the governmental technician would be to pose the requirements broadly enough so that competitive proposals could be obtained.

TOE can also press Contracting to expedite the entire process of procurement by obtaining exceptions to general rules. It may be a general rule that contracts above $100,000 are to be competitively bid, but for a particular user such as a foreign purchaser the rule may be waived so that the contract process can be expedited.

Where the usual processes of exerting pressure on purchasing isn't effective, the most drastic approach is to sidestep the governmental interface and have the function performed by an outside contractor. Thus, rather than submitting the item to purchasing to obtain the goods or services, the contracting function is shifted to an outside organization. The outside organization isn't restricted by the rules and regulations of the government so is in a position to accelerate the entire process.

As the process of generating the technical specifications has become more complex and lengthy, Technical has used each of these methods to continue processing the work flowing into TO. These processes are likely to continue as additional pressures are placed upon the unit by increases in work load or reductions in personnel.

Contracting also can adapt to increasing work load in similar ways. The contracting officer is the formal agent for developing a contract between the government and the supplier using the data provided by the Technical organization working in conjunction with the user and other sources. The contractor must determine the type of contract that would serve the government's interest the best--sole source, competitive, or some variation, incentive provisions, penalties for non-performance, quality assurance provisions to include in the contract, payment provisions and other legal protections for the contractor and the government. A complex set of choices are available to the contract officer and he may independently evaluate the recommendations of technical organization, or uncritically accept their recommendations.

As the complexity of purchasing increases, purchasing exerts pressure upon the user and technical to provide greater time buffers such as longer forward planning. Contracting also exerts pressure upon the supplier-particularly in the case of continuing sole source suppliers-to assume greater risks in the contracting relationship.

In effect, the supplier may be asked to proceed on the basis that a contract will be negotiated and to do its forward planning before a formal contractual commitment is made.

Contracting also can make temporary adjustments to increased demands by "storming" behavior. Personnel can be worked overtime during high demand periods and leave provided during low demand periods. Work orders can be queued and those lower on the queue completed as the work load ebbs off. Requirements can be ordered in importance and those of lesser importance given pro forma attention.

Policy directives that entail considerable extra work can be tested and exceptions to the directives developed. For instance, in the case of the requirements for competitive contracts, the conditions when the policy must be implemented can be clarified and when deviations from the policy will be accepted. In the case studied, where users were faced with increased lengthy requirements, both those staff personnel at the headquarters level and those at the operating level were pressing for these forms of policy clarifications and simplifications.

The time spent for documenting the steps tends to be reduced. Reporting requirements are abridged and higher risks are assumed by operating personnel on violations of procedures. Informal understandings and exchanges are developed between lower level operating personnel and higher level personnel charged with enforcing the policies.

The combinations of mechanization thru the use of word processors and thru specialization of functions provide a basis for improving the efficiency of contracting units. Extensive uses of word processors provide the simplest way of increasing the efficiency of more routine functions of contracting. The group was organized into contract teams with each team specializing to some degree. The potential for increased specialization would be possible with a larger group.

An announcement was made late in the study o a reorganization that would combine Base Purchasing with Contracting. This would provide an opportunity for increasing considerably specialization and lend itself to greater use of word processors in the operations. Since most contractshave a great number of common properties, the word processor permits minor variations to be made and the common provisions of the contract rapidly produced.

Quality Assurance also had the means to adapt to changes in work load and man power reductions. The quality assurance group is centrally concerned with monitoring the extent that the contractor was implementing the program prescribed in the contract. The quality assurance personnel have a set of mandatory checks to make some which must be performed visually on the site and some of which can be performed by evaluating the computer data or other records. As any monitoring function, it can be performed pro formally or closely adhered to.

One method of adapting to increased work load is to rely upon the contractor to a high degree to perform the tests without close checking. In this case the government employee must certify the contractor as meeting the requirements without independently assessing this fact. It shifts greater risk to the government since the contractor's responsibility is fulfilled once the contract requirements are certified as met.

Another method of dealing with increased work load is to press for greater degree of decentralization so that local conditions can be better adapted to. Or the unit can press headquarters for changes in policy to reduce mandatory checks to only ones that are viewed as critical to local personnel. Or the local unit may press for changes in the type of tests thatare to be made such as for a single observer rather than two or three observers; or rely upon computer generated data rather than visual data.

Adjustments can be made to short term increases in work load by shifting personnel to overtime during high demand periods and providing leave time during low demand periods. Queuing procedures can also be used and pro forma attention given to tests and activities of marginal value and by shifting time and attention to steps considered of central importance. Random tests may be made rather than preprogramed tests.

The group efficiency can be increased by personnel upgrading, specialization, and increased use of trainees. As the work load increases, close scheduling is necessary since the usual buffers are reduced. The system is more vulnerable to unanticipated absences, fluctuations in work load and unanticipated problems. The unit becomes more dependent upon drawing upon personnel outside the unit from central headquarters or other sources for temporary personnel.

In this unit, attention was being given to systematically addressesing these problems. Each of these processes of adapting to increased work load and reduced man power were being used. These adjustments, however, were associated with high stress within the group, dissatisfaction with the supervisor as he pressed the adjustments, and intergroup conflict with personnel on the Base. The actions that would be most helpful such as greater degree of local discretion to devise an appropriate quality assurance program was most difficult to effect.

In Contract Administration, various adjustments also were possible under varying work load. In this area, the adjustments were similar to a quality assurance. There is greater potential for adjustments in this area without substantial down grading of the function being performed. Where contract administration was involved in negotiating additional provisions of the contract, they had the same opportunities as Technical and Contracting to shift the functions to the user. The monitoring function and negotiation of price adjustments on open ended provisions can be performed with a good data base where information has been systematically collected, or reliance is upon data generated by the contractor. The unit was pressed to rely to a great degree upon data acquired by the contractor.

Short term adjustment to work load can be accomplished by shifting personnel from low level periods to high level periods. Longer term adjustments are effected by reviewing what functions of contract administration are critical and concentrating on these features and giving pro forma or random checks on other features of the contract. These adjustments were being made with the effect of reducing the costs of contract administration and increasing the risk to the government.

RECOMMENDATIONS

Expanded Study of Operations. Expanded studies are required to obtain a more complete understanding of the effects of present organizational design, centrally determined policy directives, and restrictions of and protections of the Civil Service System regulations particularly as they relate to staffing and bumping. Comparative studies are needed to contrast the way in which these factors affect operations where the units are faced with different conditions.

Studies with an expanded focus on all PM and TO units as they interface with both the user and contractor are needed particularly to assess the implications of reducing levels of manpower and increasing the work load on units. It is clear that one of the adjustments being made is to shift functions to the user and contractors as a result of increased work pressures on the governmental units. A close assessment is needed to evaluate to what extent short term costs savings are being achieved by long term increased risks and greater costs to the government.

Increasing the Discretion of Local Units. The Technical and Purchasing units are operating under severe constraints from policies issued by higher level administrative units. While there are obviously great pressures upon higher level units to adopt uniform policies on purchasing across all units in the Air Force, the means of achieving uniformity and co-ordination is highly destructive of efficiency and effectiveness of the operating units. Conflicts among groups are built in the system by these centralized policies that make it difficult for even dedicated professionals to do their jobs. An increasing amount of time is involved in working up technical specifications, setting in motion the process of purchasing the products or services, and obtaining the purchases. In other terms, the user is taking longer to obtain the supplies and services that are needed to carry out its responsibilities.

The solving of the problems involves several actions: The higher level organization should rely upon ends that it is trying to effect rather than the means to the ends in establishing policy constraints for the operating units. For example, a policy that was being strongly pressed would reduce sole source contracting and increase competitive bidding on contracts. The policy was being implemented by setting in motion a complex review and justification procedure for all sole source contracts. Contracts above various dollar levels had to be reviewed and approved by intermediate or highest level administrative offices. The financial committments of funds was constrained by controller policies and had to be reviewed by higher level officials. Each of these steps had to be done largely in sequence rather than parallel so extensive time was built in the system to determine if policies were being implemented.

If, on the other hand, a more flexible policy would be to established standards that required increasing percentage of contracts to be competively awarded in the next five years, the operating units could be given the discretion on how these standards were to be met. This would place the judgements where the greatest information is available and eliminate the time consuming review procedures. The operating units at the Base are not in a position to implement changes in procedure, but they can propose the procedures to higher level administrative personnel along with a clear statement of the problems of present methods.

Similarly, the interfacing of technical requirements, budgetary requirements and purchase requirements can be at either the Base level or at higher levels. At present, these policies are separately formulated at high administrative levels; the Commander of TO, PM and Accounting units at the Base have limited discretion to coordinate and reconcile differences among these units. Decisions must be continually shifted up to higher levels in the organization. Effecting changes in this structure is even more difficult. Again, though, the focus should be upon the ends that the Air Force is trying to achieve rather than on the means of achieving these ends in the formulation of policies that restrict the discretion of the operating commander of these units.

The operating units have limited ability to make adjustments in these structural arrangements. Again, attention should be given to proposing increased delegation by focusing upon ends rather than means while highlighting the problems under the present restrictions.

Spatial Physical Arrangements in the PM Group. The spatial physical dispersion among work sites will impact upon relationships within groups and between groups. This fact requires that spatial physical arrangements be established so that individuals and groups are physically located together who require an ongoing work relationship. In this organization, two basic activities are carried on: Those relating to the range contract and those relating to the space and missile contracts. The groups should be physically arranged so that the personnel are broken into two project groups to the extent that this is physically possible. The nature of the functions of these two projects require substantially different ways of approaching the work. Essentially, this means that all, or most of the personnel involved with the space and missile contracting would be located at the outlying site; those involved with the range contract would be located on the Base. In this case, changes can be implemented that would be helpful in supporting group relationships that are important in carrying out the job.

The formal grouping of units in departments is an area covered by Air Force Regulations and must be approved by higher level administrators; even at higher levels, officers are constrained by policy directives on the way in which a PM unit is to be formally orgainzed. It would be useful to organize these groups dealing with the range and space and missile business. During the study, a proposal along these lines was made by the administrator of the PM unit to higher level authorities. The proposal was rejected and further changes in organization were being made to emphasize functional specialization.

While these changes may be proposed again in the future, it is evident little change can be made until an evaluation is made at higher level administration in the Air Force of the consequences of requiring the same administrative structure on all units. The formal grouping of personnel along functional lines and physical grouping along project lines would create some problems for the supervisors of the units. It would probably require that a senior person be informally regarded as head of each specialized unit at the outlying base and at the Base. The formal supervisor would work with these operating heads in coordinating the functions where necessary. Similarly, one of the senior unit supervisors or other senior official would need to be designated as informal heads of each of the project groups. This places a high reliance upon an effective functioning informal organization, but it is a reasonable accommodation to a situation that is poorly formally structured.

Reward System and Staffing. The supervisors are operating within the constraints of the Civil Service System and its policies on salaries, merit increases, bidding rights on jobs, bumping rights with reductions in personnel, and central determination of qualifications of personnel. The effects of this set of regulations is to place a high emphasis upon the protection of individuals who have greatest seniority in their claim to a job in the organization and promotion to positions in the organization. However, it provides the individual low protection in his/her claim to the present job, or to the present rank. The regulations place low priority upon supervisor control of staffing and motivating of present personnel to high levels of effort. The total system sharply impedes the building of an efficient unit.

A broad number of changes in the Civil Service System is needed to provide a better balance of protection for the senior employee and the provision for controls that would enable the supervisor to carry out assigned responsibilities. These include but are not limited to a sharply reduced bumping potential when jobs are downgraded or phased out, increased discretion of the supervisor in awarding merit increases, increased authority of the supervisor to promote outstanding personnel in his unit, and greater authority to select personnel to fill vacant positions. Changes in these regulations, however, are unlikely to be made since these regulations are codified by Congress and Civil Service Commission.

Feasible actions are limited to operating within Civil Service regulations. One set of actions deals with establishing a skill hierarchy within each area and bringing trainees into these positions. A systematic program of regrading positions so that a hierarchy of grades exist within each unit would create the potential for exerting greater influence over employees. As positions were vacated by retirements, transfers or other reasons, attention should be given to establishing a hierarchy of grades within the groups. Second, all units should be involved in bringing trainees into the lower level positions. This would provide a basis for bringing in personnel with skills that are more likely to be relevant to the complex environment of the 1980's and 1990's with the revolutions in computer technology, word processors, and other technical changes in jobs. Perhaps as important, a basis is established for using the reward system to motivate and influence behavior. Trainees and those employees in midcareer are more likely to be responsive to initiatives of supervision and to changes in organization arrangements or policy revisions.

Intervention Methods.

A second approach to influencing the organization process is for the supervisor to actively intervene in the processes, expediting communication exchanges, reconciling conflicts, praising outstanding performance and buffer destructive pressures on the units. The head of the PM unit was especially skilled at intervention and made an extremely difficult situation workable for most of the employees. He set a tenor and tone for the other supervisors that was constructive and positive as they dealt with onerous constraints and high pressures for performance from higher level administrators and other parallel units.

A few additional areas of intervention would be helpful in facilitating the organizational processes. While a stress relationship is always likely to exist in the independent work flow with the centralized constraints between TOE and PM, personnel in neither unit had much appreciation for the problems of the other unit. A monthly or bimonthly meeting of supervisors and key personnel with an agreed upon agenda would be helpful. Such a regularly scheduled session would permit recurring problems to be highlighted, discussion of constraints for solving the problems and proposals for dealing with the problems jointly agreed upon.

Similarly, the spatial physical distance between the Base office and the outlying site at the space and missile program create problems of communication and intergroup relationships. The administrator could improve the relationships by a couple of symbolic and expediting acts.

Staff meetings were regularly scheduled at the Base Headquarters. These staff meetings could be scheduled alternatively at the Base and at the outlying site. This would symbolize the equal importance of the personnel and activities at the Base. Since the Administrater was particularly personable, it would provide an opportunity to interact with the employees at the outlying site and communicate his interest and attention to their activities.

Second, problem sessions with unit supervisors and key operating personnel could be regularly scheduled at the outlying site. If an agenda was agreed upon ahead of time and input solicited on problems and ideas for solving them, it would provide an opportunity for the direct expression of strong feelings on part of many of the personnel.

The staff meetings could serve this function, but the tradition of only supervisors actively participating would need to be modified.

The combinations of structural changes that are feasible and intervention methods would be helpful in solving some of the problems. However, the organization is operating under conditions of a classic level of over centralization, declining levels of supportive resources, and increasing pressures for performance. Actions are taken centrally with little input or understanding and/or concern for functioning of the units. It is remarkable that the level of professionalism that was observed is maintained under these conditions.

Broad changes are required to make striking improvements in the operations. Broad scale studies commissioned at the Air Force top levels that highlight the problems and provide feasible alternatives would likely create the documentation for effecting broad scale changes. Until then, a great deal of emphasis will have to be placed on how the supervisors can operate effectively in a poorly designed situation.

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FINAL REPORT

DYNAMICS OF TWO-DIMENSIONAL EYE-HEAD TRACKING

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DYNAMICS OF TWO-DIMENSIONAL EYE-HEAD TRACKING

by

Andrew U. Meyer

ABSTRACT

This project is concerned with two-dimensional target tracking, where eye and/or head motion is used for control. Particular attention has been devoted to a tracking method involving electrooculography (EOG) and to one using a Honeywell remote oculometer. Both tracking methods involve eye-head coordination, but in different ways. Experimental work was carried out at the tracking laboratory of the Aerospace Medical Research Laboratory at Wright-Patterson AFB. The tests, conducted with fifteen human subjects, involved tracking of targets in two-dimensional quasi-random (sum-of sines) motion. All tests were conducted at three different target amplitude (envelope) levels, in order to study possible nonlinear effects. The recorded data are being processed to obtain frequency response spectra and a statistical evaluation of the tracking performance. The tracking methods are discussed and recommendations for further research are given.

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I. INTRODUCTION:

Increasing demands on pilots for vehicle control and other functions have made it desirable to supplement the use of hands and feet for manual control by other means, especially for seconday tasks. Utilization of eye and head movement for this purpose has been considered for some time.[1-7] Potential applications may include not only navigational tasks and fire control, but also the selection of information displays or function switches.

In head pursuit tracking systems[1-3], control is exerted from signals derived from head position sensors. Visual display of the positions of both target and controlled device enables the operator to reduce their difference by corrective head movement.

Target tracking by eye movement is also possible but practical only if the head is not constrained. The Honeywell Remote Oculometer[4], based on corneal reflection, measures line-of-signt within 1 degree accuracy, permitting the head to be located anywhere within one-cubic foot of a specified location. Thus, the tracking dynamics involve both eye and head motion. The accuracy of $\pm$ 1 degree makes it possible to track without the need for visual feedback. Thus, the operator can track by simply looking at the target, relieving him from the task of conscious error correction. On the other hand, in its present state, the oculometer is rather sensitive in its operation. If operated without visual feedback, extensive calibration will be required.

A setup in the tracking laboratory of the Aerospace Medical Research Laboratory (AMRL) at Wright Patterson Air Force Base which the tracking error remained within certain bounds; it also computes the 50% CEP (circular error probability), which defines the radius about the target within which the tracking error remained within 50% of the run-time. The frequency response analysis provides not only gain and phase spectra, (in the describing function sense) but also prints out the spectra of correlated and remnant powers for target, control (response) and error signals.

The facility has been used in experiments involving head tracking by helmet-mounted sight[2,3,5], as well as eye-head tracking using the Honeywell remote oculometer[4,5,6,7]. For both methods, closed-loop gains have been reported that appear reasonably flat up to 1 Hz with half-power handwidths around 1.5 Hz[2,5,6,7]; these reports also show coherence functions* above 0.75 for frequencies up to 1.5 Hz, except for one report on single-axis eye tracking[6] where the coherence function lies between 0.5 and 0.82. High coherence function values (close to one) suggest linear behavior.

Of the above reports, one also deals with the effect of target angle size on (helmet) head tracking[2], showing that an increase of target-angle envelope causes a large increase of closed-loop tracking gain. However, this effect appears to be limited to the gain-level itself, not its function of frequency nor the frequency responses of the closed-loop phase and of the

*The coherence function, $\gamma^2 = |\text{cross power density between input and output}|^2 / (|\text{power-density of input}||\text{power-density of output}|)$ represents the proportion of input power contained in the output power. Its range is $0 \le \gamma^2 \le 1$.

(WPAFB) incorporates the above tracking instrumentation. Displays of target and visual feedback are provided in the form of red spots, projected to a large cloth screen from two low-power lasers via pairs of x-y galvanometer-mirrors. The subject sits in a chair approximately 3 meters away from the screen, which provides a visual field of approximately $\pm 20^{\circ}$ each in vertical and horizontal direction. In addition to computing equipment which is part of the tracking instruments, the laboratory features a PDP 11/34 minicomputer with associated A/D and D/A channels. The setup also contains analog computer equipment, signal generators, both deterministic and random, as well as relevant measuring equipment, which can all be appropriately connected, if and when needed, on a patch panel.

The PDP 11/34 minicomputer can be used both for target signal generation and for data analysis, for which programs have been developed by and for AMRL. Target motion can be provided from programs that calculate and generate quasi-random signals in the form of sum-of-sine waves[8,9], for given specifications. During a tracking run, the computer provides the signals driving the galvanometers for both target and visual feedback spots and receives the signals from the tracking instruments (e.g. oculometer). All signals, for both azimuth and elevation, are stored on disk for further analysis.

Data analysis capability includes programs for statistical evaluation and for computation of the frequency response of the subject's tracking performance. The statistical evaluation provides information on the portions of time during a run during which the tracking error remained within certain bounds; it also computes the 50% CEP (circular error probability), which defines the radius about the target within which the tracking error remained within 50% of the run-time. The frequency response analysis provides not only gain and phase spectra, (in the describing function sense) but also prints out the spectra of correlated and remnant powers for target, control (response) and error signals.

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coherence function (about 0.75) which all remain roughly the same. No explanation has been presented.

An increase of closed-loop gain with target-size suggests the possibility of nonlinear saturation in the feedback path of the tracking loop, perhaps in the human sensing mechanism. However, before attempting any such modelling attempt, it would be desirable to conduct a thorough experimental investigation of the target size effect (reference 2 presented preliminary data for helmet tracking on only 3 subjects). For eye-head tracking (using the remote oculometer) no results were available on the effect of target-level.

It should be noted that the AMRL tracking laboratory, including the remote oculometer, the helmet-mounted sight and the associated computer facilities, offers a unique opportunity to conduct basic experiments and comparative studies of different tracking schemes.

II. OBJECTIVES:

The objective of this research was to conduct experiments to obtain data relevant for the (later) development of a describing function model of eye-head tracking, including the effect of target-level.

Originally, this investigation was to concentrate on tracking with the Honeywell remote oculometer. However, due to unexpected delays and problems connected with a move of the tracking laboratory facility between building, that instrument did not become operational until August 8, 1979, near the end of the author's stay. When it became evident that the oculometer could not be used in time to conduct a sufficient number of tracking experiments, the author proposed a different eye-head tracking method based upon electrooculography (EOG) and proceeded to conduct tracking tests on human subjects, using the target generating and data processing facility of the AMRL tracking laboratory. When the oculometer finally become operational, tracking tests were expanded to include both oculometer and EOG tracking.

The objective thus was to conduct tracking experiments with targets varying randomly in both horizontal and vertical direction, using different target angle envelopes in order to determine possible nonlinear behavior. The recorded data will be used in a later project to model EOG tracking in terms of its describing function representation, and to compare EOG tracking with oculometer tracking.

Moreover, all oculometer tracking experiments were conducted with and without visual feedback, in order to compare performance of tracking by just looking at the target (without visual feedback) and tracking (with visual feedback) where the subject must consciously control the feedback image to align with the target image. EOG tracking is practical only with visual feedback.

III. EOG TRACKING

Electrooculography (EOG) is a method for measuring (both horizontal and vertical) eye orientation[9,10]. Its chief advantage is its simplicity; other assets include its fast speed of response and the large angular range. On the negative side are problems with d-c drift of the EOG responses and inaccuracy.

It is not the intention here to claim EOG as any better alternative to existing trasducer methods for tracking, but rather to examine some basic properties of EOG tracking. The EOG tracking scheme investigated in this research calls upon different tasks for the human operator than other methods. They involve head-eye coordination and EOG tracking tests may provide a tool for the study of their dynamics.

Since eye-position sensing by EOG is inherently inaccurate, one may be tempted to dimiss EOG for use in target tracking. However, one should realize that the accuracy of any (eye-position) sensor will be of very little significance if its output is used to control the visual feedback display. It is then the human operator who performs the measuring by perceptual means. This, of course, is true for any tracking scheme incorporating visual feedback including head-tracking. The sensor-inaccuracy will merely affect the open-loop gain, with relatively little effect on the (closed-loop) tracking performance. Likewise the drift of the EOG potential does not affect the tracking accuracy and should be tolerable as long as it stays within a reasonable range in the visual field. Though the drift was tolerable for the EOG tracking experiments performed in the laboratory, it is believed that it can be reduced by careful choice of electrodes; even if not, its effect can be reduced by electronic means.

Electrooculography is based upon an electrical d-c potential difference between the front (positive) and back (negative) of the eye. Electrodes placed across an eye will pick up a d-c potential roughly proportional to the eye orientation angle, with a sensitivity of the order of 20 microvolt per degree.

In the tracking experiments conducted during this research, vertical orientation (elevation) was picked up from electrodes placed above and below one eye, whereas horizontal orientation (azimuth) was picked up by electrodes placed outside of both eyes. An electrode placed on an ear lap was connected to the ground. The vertical and horizontal electrode pairs were connected to d-c amplifiers which, in turn, drove the mirror-galvanometers to provide the feedback display spots.

Depending on the polarity of the feedback connection, two different modes of EOG tracking are possible, which shall be called (a) eye control mode and (b) head control mode, to emphasize the dominant motion involved.

(a) Eye Control Mode: Here, eye motions causes the feedback display spot to move in the same direction, when the head is fixed. However, when the eye line-of-sight is fixed, head motion will cause the display spot to move in the opposite direction. It will thus be natural for a human to try tracking by eye motion, while keeping the head as steady as possible, except for corrective control motion in the opposite direction.

(b) Head Control Mode: Here, the display spot is moved in the same direction as the head motion (when the eye line-of-sight is fixed), or in direction opposite to eye motion (when the head is fixed). In this mode, it turns out to be natural to use head motion for tracking, unconsciously using small eye motion for corrective control.

It was found that the head contro mode is easier to perform, at least for tracking tasks requiring freedom of head position. It was therefore decided to devote the experimental work in this project to the head control mode.

Furthermore, it was decided to perform the experimental series with an overall open-loop gain of one. The gain adjustment is performed as follows: The subject is asked to keep his head in a fixed position and to alternate his eye fixation between two loactions on the screen (12 degrees apart from each other), while the amplifier gain is adjusted such that the display spot controlled by the eye movement alternates over the same distance (though in opposite direction for the head-control mode). The subject is instructed not to pay attention to the display spot during the calibration procedure. It is also possible to bias the display such that it is away from the subject's view during calibration.

The same procedure can be used to obtain any other gain value. The unity gain chosen for this experimental series appears to be a reasonable compromise between "loose control" (for too low gain) and sensitivity to disturbances (for too much gain). However, more investigation will be required to determine the optimum choice of gain.

IV. EXPERIMENTS

Tracking runs were recorded for 15 subjects (9 female and 6 male) between the ages 18 and 62, of which one subject was tested, in a preliminary series, for the effect of random target forcing functions of different break frequencies. Fourteen (14) subjects were tested for EOG tracking, each at three different target amplitude envelopes (6^{o}, 9^{o} and 12^{o}). Of these, 6 subjects were also tested for tracking with the Honeywell remote oculometer, also at the same three target amplitude envelopes. The oculometer runs were all conducted with and without feedback display.

In order for the subject to be able to distinguish the target spot from the feedback display spot, the latter was smaller (approximate diameters were 12 mm and 3 mm respectively; the screen was about 3 meters away from the subject). The target was driven in both azimuth and elevation by sum-of-sine functions (10 frequencies), simulating random motion[8]. The frequency ranged between 0.1 and 3.0 Hertz, with a (6 dB) break frequency of 0.8 Hz in all runs for 12 subjects. After earlier EOG tracking runs on two subjects were performed with forcing functions of 1.0 Hz break frequency, it was found that 0.8 Hz would be more realistic.

EOG tracking, as described in Section III, involves a certain amount of head-eye coordination and constitutes a somewhat more difficult task for the human operator than oculometer tracking (especially oculometer tracking without visual feedback). It therefore requires a certain amount of training. Among the 15 subjects, the time required to acquire a reasonable tracking skill varied between 10 and 30 minutes. Scheduling constraints did not permit any longer training periods which, perhaps, may have improved the tracking scores.

After the training period, each subject did seven tracking runs, each lasting 91 seconds. The first of these, considered a practice run, was performed at a target amplitude envelope of 6 degrees. The subsequent six runs consisted of two runs each of target amplitude envelopes of 6°, 9° and 12°, their sequence being permuted. Also permuted were three forcing functions with equal amplitude characteristics but different (randomly selected) phases (except for each initial (practice) run which used a forcing function differing from the others by its break frequency of 0.7 Hz).

The tracking tests with the Honeywell remote oculometer were performed on six of the subjects. For each subject, eight oculometer runs were performed; four each without and with visual feedback. For each set of four runs, the first (practice) run had a target amplitude envelope of 6^{o}, the other (regular) three runs were perfomed at 6^{o}, 9^{o}, and 12^{o}, the sequence being permuted, as was the (same) set of three target forcing functions used in the EOG experiments.

For the oculometer runs with visual feedback, on open-loop gain of one was used, achieved by calibrating the equipment such that the line-of-sight is aligned with the feedback spot (this is part of the normal oculometer calibration procedure).

In view of the author's limited time of stay at the laboratory facility, inherent to a summer program, it was decided to concentrate on the experiments and data collection and to relegate any detailed analysis to a subsequent project. All test data and relevant analysis programs are on magnetic tape which is to be used as the basis for data analysis at the author's institution (see Sections II: Objectives and V: Recommendations).

V. RECOMMENDATIONS:

(1) Evaluation of Present Data:

Recommendations (a), (b) and (c) below pertain to work to be performed under a minigrant project being proposed:

(a) Completion of computer analysis for all tracking runs performed during the summer 1979. Evaluation of printout data including careful screening for data acceptability. The presentation of the results will be in terms of statistical evaluation and frequency response data for the tracking runs.

(b) Effort to interprete the frequency response results in terms of a simple describing function model. The effect of target amplitude levels is to be considered.

(c) The above analyses are to be conducted for EOG tracking as well as for oculometer tracking, both with and without feedback display. The results will provide information relevant to a performance comparison between the three tracking schemes.

(2) Further Recommendations:

The recommendations given below would go beyond the above data analysis and evaluation:

(d) Investigation of accuracy requirements for any tracking scheme when feedback display is used. The AMRL tracking laboratory is ideally equipped for such a project in which the gains and outputs of a reasonably accurate head (helmet) sensor and/or line-of-sight sensor (oculometer) can be modified by constant or random errors. Since the actual error-sensing is performed by the human operator, instruments (such as oculometer, helmet sensor or EOG sensor) merely serve as control actuators. Errors in instrument sensitivity affect the open-loop gain but may have little effect on the steady-state tracking error. Moreover, human adapation may possibly have a compensating effect on the open-loop gain itself. Likewise, any instrument output bias including drift does not directly affect the steady-state tracking error. It would be desired to find out how accuracy and dynamic performance of tracking (with feedback display) are affected by changes in instrument gain, as well as by bias and drift. Such a project will provide data needed to establish specifications for sensing instruments to be used in practical tracking schemes.

(c) Investigation of the effect of open-loop gain in tracking schemes with feedback display: Whereas Recommendation (d) above pertains to accuracy effects of instrument gain and bias, this recommended effort seeks to establish optimum open-loop gain for given tracking tasks. All experiments conducted this summer with EOG tracking and oculometer (with feedback display) involved unity loop gain. This choice appeared "reasonable" but may not necessarily result in optimal tracking performance.

(f) Reduction of drift and its effects in EOG tracking: search or design of electrodes for lowest possible drift. Even with presently available electrodes, drift may not be objectionable, as long as the subject can comfortably exert control. Electronic circuitry can be designed to compensate for drift or to automatically reset the d-c level when the drift exceeds a certain level. Another improvement can be obtained by a circuit that locks the feedback display in case of events such as blinking (such circuitry exists in the Honeywell remote oculometer). One of the problems of any tracking system involving feedback display is the temporary loss of the feedback display. This will cause the subject to go into searching motion. This happened during some of the experiments conducted during the summer, causing reduction of overall tracking performance. It is possible, however, to prevent this from happening by limiting the display such that it never leaves the boundaries of the visual field.

(g) Model study of eye-head tracking: The tracking schemes considered in this research, including oculometer, with and without feedback display, as well as EOG tracking, all involve human eye-head coordination, though each in different ways. For eye tracking itself (with fixed head position), several models have been proposed[11,12,13,14]; however, they may serve, at best, as guides in the search for a model of eye-head tracking, which must include the dynamics of eye-head coordination[15,16]. An important property desired of a model is the identifiability of its element from data of properly chosen tracking experiments.

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1979 USAF - SCEEE SUMMER FACULTY RESEARCH PROGRAM

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FINAL REPORT

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Date: 17 August 1979

Contract No: F49620-79-C-0038

OPTIMIZATION OF THE FEED FORWARD TECHNIQUE FOR BEAM CONTROL IN THE APT

by

Jerrel R. Mitchell, PhD

ABSTRACT

The Airborne Pointing and Tracking (APT) System is an integral part of the Airborne Laser Laboratory. In order to reduce the susceptability of the system to noise and disturbances, studies were initiated in which the Automatic Alignment System (AAS) was used in a feed forward technique.[1,2] The work presented here is an extension of this.

A filter is placed in one of the paths between the APT and the AAS. For various cases of a "fly-by" type scenario, the coefficients of the filter are optimized so as to minimize the root mean square error (RMS) of the beam angle. This is done in the frequency domain with a computer code. The results show that with the feed forward scheme and with the optimal filter the RMS error can be reduced from ten to a hundred fold.

ACKNOWLEDGMENTS

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I would like to especially thank Captain Robert Van Allen who provided me with a challenging and interesting assignment and who made many helpful comments and suggestions throughout the duration of the project. I would also like to thank Dr. Paul Merritt and Major Carey O'Bryan for stimulating discussions and a working atmosphere that was both mentally and physically stimulating.

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FINAL REPORT

PREDICTING THE IMPACTS OF USAF PERSONNEL CUTS

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Date:	August 7, 1979
Contract No:	F49620-79-C-0038

PREDICTING THE IMPACTS OF USAF PERSONNEL CUTS

by

William T. Morris

ABSTRACT

This research program aims at the development of methods which will offer simple, practical assistance to Air Force Managers involved in:

1. Predicting the impacts of personnel cuts as a part of the budget justification process.
2. Managing the process of taking personnel cuts in their organization.

The program outlines the development methods for the specific case of Air Logistics Centers based on imexpensive modifications of existing manpower management systems. It then addresses the more general problem of the development of methods for coping with cuts at other types of USAF organizations.

ACKNOWLEDGMENTS

The author wishes to express appreciation to the Air Force Systems Command, The Air Force Office of Scientific Research, and the Southeastern Center for Electrical Engineering Education for creating and administering the outstanding research opportunities of which this effort is a part.

Special appreciation is expressed to the following extremely helpful persons; in the Air Force Business Research Management Center, Colonel Martin D. Martin, Major Lyle Lockwood, and Captain Paul Gross; in the Air Force Logistics Command, Major Robert Huber, Captain James Vitelli, and Captain Lloyd Watts.

My research colleague, Captain William L. Glover of the Air Force Business Research Management Center was patient, experienced, tactful, helpful, and highly skilled in helping me learn about the Air Force environment. It was a privilege to work with him.

I. INTRODUCTION

Increasing concern over personnel cuts has become a fact of life in the defense management community. Many believe that manning level reductions pose a serious threat to our defense posture, but the magnitude of this threat and the balance between cost savings and effectiveness reductions are matters of experience, judgment, and speculation. Personnel reductions are now achieved by attrition, across-the-board cuts, seniority-based policies, organizational unit transfers, contracting out, reassignment of functions, and by various processes of negotiation. This research program does not begin with the assumption that these processes are necessarily unreasonable, only that little systematic, quantitative evidence is available as to their impacts on national security. Participants in the manpower reduction process indicate that they have available little in the way of principles, insights, or empirical relationships on which to negotiate a reasonable balance between saving and losses of mission effectiveness.

In planning this research program, it is useful to break this general problem into two more specific management problems:

(1) In the budget justification process, how can one provide credible quantitative predictions of the impacts of specific personnel cuts?

(2) In the event that cuts are required, how can one most effectively management the process of making them?

II. OBJECTIVES:

This research program addresses both of these questions by outlining a detailed plan for confronting the following basic research issue:

> Can methods be developed which will be useful to Air Force Managers in predicting the effects of personnel cuts and in managing them reasonably?

It may be helpful to emphasize that the program is concerned with methods which a specific manager might use in a specific organization particularly adapted to the needs of that organization and of the manager. The goal is to develop management tools, techniques, or systematic processes, not to generate empirical evidence on the consequences of any particular kind of personnel cut or to recommend the way of managing manpower reductions.

It may be helpful also to take note of certain minimum criteria which such methods must meet in order to be useful to Air Force Managers:

(1) For budget justification purposes, impact predictions must be quantative, brief, and backed up by some sort of credible data and methodology.

(2) For both budget justification and for management purposes, it is important to have identified and qualitatively considered a richer range of impacts that can typically be expressed in a short impact statement.

(3) When cuts are threatened, no organization is in a position to embark on long, expensive research undertakings. A methodology which suggests to a manager that a large scale, high resolution simulation of the entire

organization be created, is probably not going to be very helpful. To be useful, methods must require only modest amounts of data collection and analysis. They must rely to a great extent on existing, credible data systems.

(4) To be useful, impact predictions must be credible in the budget process. The initial hypothesis of this research program is that typical bases for producing impact statements may be ranked in order of <u>increasing</u> credibility as follows:

- Judgments made by individual managers.
- Consensus judgments reflecting the experience of groups of managers.
- Models using data gathered by operational audit methods (See AFLCR 25-8)
- Models using data from official systems having updated, audited inputs and an established reputation.

(5) The management strategies explored must be more sensitive and more responsive than those traditionally used in government organizations.

III. SIMULATION

To provide a starting point for further model development, a computer model which captures part of the structure of the E841 Manpower Management System is proposed. This model will be essentially a simulation of the E841 System which will permit a host of "what if" studies to be run by management using a system having established credibility, an extensive data base, and audited, adaptable inputs. In this way, modeling can get under way without the prohibitive demand on the client's computer resources that would be involved in using the E841 System itself to make impact studies.

For purposes of this study, the basic relevant function of the E841 system is to accept workload projections from the organizations served by an ALC and use these to predict the manpower equivalents which would be required to accomplish this workload. The proposed model or simulation simply removes that part of the system which does this and reproduces it in the form of another program. The model or program is then modified through the addition of certain key assumptions to permit the reverse sort of question to be studied; "What will be the effect on the workload accomplished if various kinds of cuts are made in the manpower equivalents available to the ALC?"

It should be noted immediately that the workload implications of a cut in manpower equivalents cannot be usefully interpreted as work that will not be accomplished. It is a suggestion to management that, under the ALC operating conditions captured in the E841 model, a predicted amount of work will not be accomplishable in the usual, routine way. The prediction would suggest to management the amount of work that might have to be accomplished on overtime, transferred to another organization, or delayed. It might also be an indication to management of the amount of additional effort personnel would be required to put forth, or the amount of methods improvement and procedural streamlining that would be called for. While this may be of considerable use in some management contexts, more realistic types of impact predictions are sought in later sections.

The basie research questions here are:

(1) Will such a simple model be useful? Is a more elaborate model warranted?

(2) Can this serve as a step in the development of a more elaborate model of an ALC?

Two types of runs will be possible with the simulation, referred to as forward (FE841) runs and backward (BE841) runs. FE841 runs will do exactly what the E841 system itself does in predicting manpower requirements. This type of run is used to validate the simulation against the E841 itself. These runs permit the easy exploration of what would happen to required manpower equivalents for all sorts of workload modifications.

BE841 runs permit management to make manpower equivalent cuts and predicts the workload decreases that these would imply. It will be possible, given certain kinds of management preferences about non-routine handling of workloads, to explore"good" and "not so good" ways of taking a cut. Caution: BE841 runs permit (and require) management to make a variety of assumptions not present in FE841 runs.

IV. MODELING A BUYING SECTION

This section outlines the methods which may be used to develop a group of increasingly rich and complex waiting line models of the buying work centers at an ALC. These models, the first of which are extremely simple, have several useful properties:

(1) They permit the capturing of the non-linear effects of personnel cuts and the expression of these effects in terms of workload and turnaround time.

(2) They can be tested and quantified using data routinely available through the J041 system.

(3) They suggest a systematic program of model enrichment, moving to more complex levels if the data seems to require it. They permit one to ask the basic research question, "Will relatively inexpensive analytic models suffice for the client's purposes, or will it be necessary to develop a large scale, high resolution simulation of an ALC?"

Modeling begins with the study of a buying section on the hypothesis that the buying activity experiences the most sensitive and important impacts when personnel cuts are made.

Personnel cuts of interest at ALC's are small, long lead time reductions on the order of one or two people at a time. These cuts are made by attrition and, it is hypothesized, the induced management response is simply to redistribute the workload among those remaining. Large reductions in personnel are more likely to induce a management response involving reorganization, extensive changes in methods, elimination of functions, and automation.

Hypotheses like the above seem to reflect the best judgment of experienced managers in the acquisition process. A number of such hypotheses are used to guide the modeling program outlined below. It is useful to keep in mind, however, that they are hypotheses which may or may not be confirmed as the investigation progresses. They are useful starting points.

When, in the "typical buying section," the number of buyers is cut, those remaining experience an increase in workload. The rate at which the section chief assigns them PR's must, in the perception of a remaining individual buyer, go up. The buyer may respond to this in a variety of ways, but for the present we will concentrate only on those responses which are reflected in terms of the buyer's production rate, the rate at which actions are completed.

The buyer, experiencing an increased workload, may:

- simply work harder
- shift some of the load by relying more heavily on clerical support
- work less hard to justify past efforts, to express feelings toward the organization, to demonstrate the impacts of personnel cuts
- omit functions, tasks previously performed
- prioritize PR's in the backlog
- consolidate PR's into procurement actions, elect simpler types of actions
- make more mistakes, resulting in an increasing number of administrative modifications which further increase the workload

The chief of the buying section, it is hypothesized, spreads the increased workload per buyer in a way which at least roughly takes into account:

- existing buyer backlogs
- equity among buyers
- special abilities and experiences of particular buyers

As a result of the personnel cut and the increasing load on the remaining buyers, turnaround time will begin to ruse. Turnaround time is defined as the time between the arrival of a PR at the section and the completion of a procurement action such as getting out a contract. As turnaround time grows, two other effects come into play which induce still further growth in the workload:

(1) Increasing turnaround time is reflected in longer delivery lead times. These in turn cause the computer based portion of the acquisition system to automatically generate additional PR's in an attempt to avoid shortages.

(2) Increasing delays cause customers to order earlier and more frequently, causing the system to further experience a classical "Industrial Dynamics" workload surge.

The initial modeling question is whether or not it will provide useful impact predictions to model a "typical buying section" staffed by "typical buyers." This is the basic research question which underlies the program outlined below.

Presumably the effects of a personnel cut depend on such things as the section chief's management style, the perceived threat to job security among those remaining, the anticipated duration of the increased load, the method by which the cut was made, the information shared by management, and the buyer's perception of how his response will influence his job security and promotion possibilities, to name a few. To model a typical buyer is to assume that these differences, when averaged across buyers and buying sections, will not lead to useless impact predictions. Are the responses of buyers sufficiently similar across buyers such that an "average" model will suffice? Alternatively, will it be necessary to categorize buyers according to their responses and develop multiple buyer models? This question is to be approached in two steps:

(1) Structured interviews with experienced section chiefs and buyers are expected to indicate whether it would be useful to go ahead with a quantitative analysis.

(2) A series of J041 based studies designed to reveal individual buyer responses under increasing workloads. It is the judgment of the client that buyer responses are likely to be independent of whether the workload increase results from increased customer demand or from a personnel cut.

While the assumptions underlying the following model seem warranted on the basis of preliminary discussions, they must remain the subject of active investigation.

Rather than reproduce a large amount of technical material, we will refer to relevant page numbers in:

Giffin, Walter C., <u>Queueing: Basic Theory and Applications</u>. Grid Publishing Co., Inc., Columbus, Ohio, 1978.

for the equation systems and computer programs which are likely to be useful in enriching this approach to modeling a buying section. This book contains some unique, practical methods of special concern in this effort.

The first step is to model the buyer simply as a Poisson input, negative exponential service time waiting line system. (Giffin, p. 97) Both prior logical considerations and a qualitative examination of buyer activity suggest that this is at least a plausible set of assumptions. Long run steady state predictions are appropriate for manpower planning. The behavior of the section chief in regulating buyer workload suggests that buyers may be considered as independent waiting line systems. The use of an adjustable level of base flow is used to fit the model to the observed facts that buyers do not run out of work and section chiefs try to maintain something like a reasonable backlog. Without this division of flow into basic and variable, the Poisson model will indicate more variance in the input than is actually experienced.

When the system saturation condition occurs, backlog growth rates are simply modeled as the difference of two Poisson variables, the number of PR's flowing to the buyer less the number of actions completed. These are taken to be independent random variables in the saturated condition and thus the mean of the difference is taken to be the difference of the means and the variance of the difference is the sum of the variances.

One possibility that should be considered in cases where there are multiple levels of priority making up a significant portion of the section's work flow is the use of priority waiting line models which emphasize the effects of prioritization. (Giffin, p. 241).

Some section chiefs may behave differently than the assumptions which underlie the numerical example, and it may become appropriate to test the multiple channel family of models for a buying section as a whole. This will be especially true should the section chief hold back most of the PR's in the section's backlog, rather than let backlogs build at the buyers' desks. (Giffin, p. 100).

Probably one of the least sensitive aspects of these models is the actual form of the arrival distribution and the service time distribution. It is well known that the steady state results used in this application are extremely robust in the face of departures from the precise assumptions about input and service time distributions. (Giffin, p. 148).

The most powerful enrichment of this group of models for our purposes lies in the direction of making the mean arrival rate and the mean completion rate dependent on the number of PR's in the buyer's backlog. This will permit the full representation of:

- the section chief's policy of regulating work flow
- the full range of possible buyer responses to various backlog levels
- the effect of induced workload consisting of administration modifications, computer generated PR's and delay stimulated order rate increases from customers

The question of whether there is an "optimal" backlog for a buyer is one of special interest to the client. This problem will be examined in more detail below, but it is worth noting here that this direction of enrichment will facilitate modeling the optimal workload problem in a direct way. These enrichments may be made through the use of the Hillier-Conway-Maxwell pressure coefficient models which provide complete flexibility. (Giffin, p. 119). These models do not have closed form solutions in most cases, but fortunately an effective computer program is available for their numerical solution. (Giffin, p. 321 provides the full program listing).

When a personnel cut is made a step increase in workload (on the average) is experienced by a buyer. It would be of some management interest to know the transient behavior of the system or the order of magnitude of the relaxation times. Unfortunately, solutions of even the simplest transient equations are complex. The graphical results given by Giffin (p. 139) at least support the assertion that from a long range planning viewpoint, the resulting changes in the system are likely to appear rather quickly.

It should be kept in mind that in exploring this program of enrichments of the basic waiting line model, we are really looking at the basic research question of whether or not these relatively inexpensive models will provide useful results. If the answer emerges in the negative, then the next steps should probably be in the direction of developing detailed simulations of buyers and buying section. This undertaking is, of course, certain to be considerably more expensive and time-consuming.

V. OPTIMAL BUYER BACKLOG

The concept of optimum stress suggests that there is a level of stress of backlog which, in a man-paced operation, will maximize productivity.[1] As backlog or in-process inventory ahead of the operation goes down, the operator slows his pace in order not to run out of work. As the backlog goes up, the operator speeds up in order to slow the rate of backlog growth. If, however, backlog becomes too high, the operator "gives up" and production rate levels off or perhaps even declines. There is surprisingly little real evidence on this hypothesis and very little has been done with it in the design of production systems. Two extensive studies in public sector contexts show cases where operators, in these cases clerks accepting payments from lines of clients, were largely insensitive to the backlog they faced. One unpublished USAF study suggested that productivity in the modification of aircraft did slow as the number of aircraft awaiting modification on the ramp went down.[2] Since the section chief in a buying organization is in a good position to regulate the workloads and backlogs of individual buyers, this question is of considerable importance.[3]

It is also a difficult phenomenon to study since:

(1) Direct experimentation is precluded by the reactive nature of backlog manipulation and observation.

(2) Buyers are likely to be subject to considerable individual differences in the responses to backlog.

(3) Backlog response effects are likely to be swamped by other influences such as perceived duration of a high backlog condition, section chief management style, peer pressure, and the probable transient nature of any marked reaction to a big backlog.

However, the data available in the J041 system provides an ideal opportunity to investigate this question and the section chief is in an excellent position to use any results which may be developed.

The section chief knows, through the use of the J041 system, what each buyer's backlog is at any time. Among the modes of control which might be chosen by the section chief are:

(1) Regulate the flow rate of PR's to a buyer so as to achieve some specified weekly or monthly average backlog.

(2) Regulate the precise number of PR's assigned to a buyer so that a specified maximum backlog is never exceeded nor does the backlog fall below a specified minimum.

(3) Regulate the number of PR's assigned so that an exact specified backlog is maintained.

The buyer may respond in a variety of ways including:

(1) A steady state response which depends on the weekly or monthly average backlog.

(2) A steady state response which depends on the actual backlog at any moment.

The buyer may, of course, exhibit transient responses but the possibility of documenting these and using them for management purposes seems somewhat expensive at the moment.

Three steps are involved in approaching this question:

(1) Structured interviews with experienced section chiefs should reveal whether or not they have an intuitive concept of optimum backlog and make use of it in assigning PR's. If the buyer response phenomenon is marked, it is highly likely that section chiefs will be fully aware of it. These interviews may also yield some clues as to the existence of systematic individual differences

in response patterns among buyers.

(2) Steady state models of the Hillier-Conway-Maxwell pressure coefficient family may be constructed and solved (Giffin, p. 119) for various combinations of buyer response mode and section chief control mode. These models may be used to derive optimal control policies.

(3) A broad survey of the data available in the J041 system should yield ample data on buyer productivity at differing backlog levels. Although one cannot know what other conditions may have been influencing buyer responses, it is clearly worthwhile to do a rough analysis of this data to see if any systematic buyer response patterns can be detected. It would clearly be useful to obtain such data under conditions where the section chief was not already controlling buyer backlogs and finding these conditions may present some practical difficulties. At the very least, however, an initial study may be able to detect whether or not buyers typically respond to very high or very low backlogs.

The J041 data system provides the basis for the studies needed to test the hypotheses raised above and to quantify the resulting models for application. In addition to the study of buyer response to backlog outlined above, it is necessary to test for the following workload effects:

(1) The way in which increasing workload is associated with increasing numbers of administrative modifications.

(2) The way in which increasing workload is associated with increasing numbers of computer generated or customer generated PR's.

If these effects appear to exist, it will then be important to know whether they are roughly similar across buyers or whether it will be necessary to search for ways of classifying buyers into similar response groups.

In each case the studies should proceed in three stages:

(1) Structured interviews with experienced managers and buyers to obtain judgments as to whether the effect does exist and judgments as to the time, section, and buyers for which the data is most likely to be revealing. Considerable guidance will be required here to avoid getting data which occurred under "special" conditions likely to mask out the effect being investigated.

(2) A rough preliminary study to get a gross indication of whether the effect exists, whether interpersonal differences and intersectional differences exist, and a general set of estimates of the variability of the data. This will permit reasonable plans to be made as to the design and sample sizes for more careful and definitive studies.

(3) Execution of careful designed studies to provide an initial set of relationships to be used in the impact prediction model.

Finally, the J041 data will provide the basis for the initial validation experiment for the impact prediction model. A small number of buying sections must be found if possible, where personnel cuts have actually occurred in the recent past. For each of these sections, the model is calibrated to give at least "order of magnitude" agreement with backlogs and turnaround times before the cuts. The model is then used to predict the impacts of the cuts and the quality of the predictions is assessed by matching them against the observed data for the sections after the cuts. This provides the basis for the initial set of enrichments to the impact prediction model.

The final step of putting these two models together presents some complexity and will doubtless require some exploration and testing. It seems sensible, however, to begin with the simplest approach which does involve some approximations and reliance on some average values which may later need refinement.

The first step is to bring the buying section model into rough agreement with the backlogs and turnaround times observed in a particular buying section selected for study. We begin by making the assumption that a PE is equivalent, in the FE841, BE841 model, to a buyer in the buying section model. The load on a buyer is then defined as the average end item workload arrival rate divided by the number of buyer PE's available to the section. The accomplishment rate of a buyer is defined (in a consistent but approximate way) as the average work unit production count per month divided by the buyer PE's available to the section. This definition assumes that the buyers are never idle during the study period and that workload conditions are "normal". Normal must simply be interpreted as conditions ordinarily, typically experienced in the section. This approach seeks to avoid becoming involved with the E841 standards, efficiencies, and availabilities, and looks at the data in the simplest possible way. It is most important that the section being studied not be at or close to the saturation point.

Using these values of the load on a buyer and accomplishment capability, the base flow is set at zero and the buying section model is used to predict backlogs and turnaround times. These are then matched with the corresponding observed values. If the fit is satisfactory (considerable client judgment is involved here since the basic criterion is the credibility of the impact predictions), the models are compatible and ready for use. If not, then it would probably be useful to try:

- setting the base flow at the observed minimum monthly load per buyer PE
- setting the backlog associated with the base flow at the minimum observed backlog level

and then using the buying section model to compute the turnaround time for the variable flow and the variable flow backlog. The sum of the base flow and variable flow backlogs should be of the same order of magnitude as the observed backlog. The base flow turnaround time should be somewhat higher than the observed overall average turnaround time. This sort of tuning can be repeated using various level for the base flow and estimates of the backlog associated with the base flow, until a satisfactory fit is obtained.

VI. RECOMMENDATIONS

The task mutually agreed upon for the Summer Research Period was the formulation of a broad research program and the development of basic conceptualizations and approaches. It was understood from the outset the work would involve largely the planning phases of the research program rather than the detailed data collection and analysis activities which, it is hoped, would come later.

The formulation of this research program has involved considerable study of the Air Force environment, exploration of alternative research approaches, and evaluation by Air Force management personnel. The results appear, in the judgment of the author, to support the following recommendations.

Research efforts in several areas appear to be not only possible, but of potential benefit to the Air Force. These areas include:

(1) The simulation and modeling of manpower reduction impacts at an Air Logistics Center.

(2) The use of an impact chain methodology to demonstrate the possibility of making useful predictions in several dimensions of the impacts of manpower reductions at support work centers.

(3) The development of management guide cataloging the anticipated behavioral effects of manpower reductions.

(4) The use of structured group processes as the basic participative methodology for constructing impacts chains and for developing measures of output and productivity.

(5) The formulation and field testing of a general impact prediction methodology which may be of significant use to Air Force managers.

(6) The development and field testing of a management planning guide outlining the basic dimensions of policy options which may be used to effectively cope with personnel reductions.

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FINAL REPORT

ATTEMPTS TO SIMULATE "REALISTIC" ATMOSPHERIC MOTION WITH A SIMPLE NUMERICAL MODEL

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ATTEMPTS TO SIMULATE "REALISTIC" ATMOSPHERIC MOTION WITH A SIMPLE NUMERICAL MODEL

by

Stephen Mudrick

ABSTRACT

A previously developed, three-dimensional, numerical model is used to simulate the development of atmospheric cyclone waves. The initial conditions for the integrations consist of an east-west oriented atmospheric jet which varies only in the north-south and vertical directions, upon which is superimposed a perturbation of a given east-west wavelength. Attempts are made to increase the realism of the simulations by increasing the realism of the initial conditions. Three different approaches are used: a) The amplitude of the superimposed perturbation is increased greatly from that used previously, thus introducing more north-south wave amplitude in the upper-level flow; b) the wavelength of the perturbation is taken to be different than that associated with the fastest growing perturbation, and c) an east-west oriented surface frontal zone is included in the initial state. These attempts are only partially successful with approach b) yielding the best results.

The use of the more realistic initial conditions provides a more stringent test of a short wavelength filter developed at AFGL by Dr. R. Shapiro.

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I extend my thanks to all my friends at the Dynamics Branch at AFGL for making my visit as enjoyable as it was. A special thank you is extended to Ralph Shapiro, who made this work possible. Without the aid of Donald Aiken none of the computing would have been possible and without the discussions and guidance of Ralph Shapiro, Samuel Yee and Ken Yang the summer would have been far less interesting and fruitful.

I. Introduction:

Some time ago, Ralph Shapiro, branch chief of the Dynamics Branch, AFGL, developed a short wavelength filter for numerical weather prediction applications (4). The version of that filter used with this work, a "third order" filter, is strongly scale dependent, removing two-grid interval waves completely while effectively leaving unchanged waves longer than four grid intervals. While employed at AFGL (1973-1976) I tested the usefulness of the filter by using an atmospheric simulation model developed for my thesis work. The model can simulate the evolution of cyclone waves, and simple cases were used for the tests. Surface frontal zones formed toward the end of the simulations (2,3) and the filter was considered to have worked well.

Since leaving AFGL I have been using this and other atmospheric simulation models for other purposes. As part of that work I have been interested in running the models with more realistic, i.e., more complicated initial conditions, which hopefully would lead to more realistic simulations. In particular, I have been interested in why, in many simple cases run so far, warm fronts tend to be stronger than cold fronts. The opposite seems to be true, at least over the U.S. I also wanted to put strong surface frontal zones into the initial conditions.

Having more complicated initial conditions, especially having a surface frontal zone present initially in the integrations, would provide a more rigorous test of the filter in order to see if the front remained relatively strong or if the filter gradually "washed it out". I thus came to AFGL with plans to attempt the development of more realistic initial conditions as well as to perform a further, more stringent test of the Shapiro filter.

A description of the numerical procedure used now follows. The atmospheric simulation model, a three-dimensional primitive equation model called 3DPE is described in (1) and (2). The three components of wind are u, the east west (x) component, v, the north-south (y) component and w, the vertical (z) component. Temperature is carried by b, the "buoyancy", a quantity analogous to potential temperature. Buoyancy will be referred to henceforth as temperature. The pressure p also is needed. Another model, similar to

3DPE but based upon a simplified set of quasi-geostrophic equations, was prepared for the AFGL visit but lack of time precluded its use.

In order to step forward 3DPE in time, we need complete fields of u, v and b at a given time, i.e., $u = u(x,y,z)$, etc., at a given time. The model then predicts new values of u, v and b for one timestep later (a typical timestep is 10 minutes). The filter is used once each timestep on the u, v and b fields. The process is then repeated. The calculation of p and w is necessary at each timestep during this process.

The entire proceudre is thus based upon an initial value technique so the model needs initial conditions, i.e., complete fields of u, v and b, at the starting time. The procedure used in generating initial conditions is based upon two parts--the choosing of a basic state and the subsequent calculation of the perturbation fields. The initial (at time t_o) fields of u, v and b can be written as follows:

$$u(x,y,z,t_o) = U(y,z) + u'(x,y,z,t_o)$$
$$v(x,y,z,t_o) = v'(x,y,z,t_o)$$
$$b(x,y,z,t_o) = B(y,z) + b'(x,y,z,t_o).$$

The "basic state" wind thus is assumed to be an easterly flowing jet of air that can vary meridionally (in y) and vertically (in z) but not zonally (in x). Use of the thermal wind relation provides an appropriate B(y,z) to match the U(y,z). There is no basic state v or w. The basic state is chosen so that it is inherently unstable in the sense that a small superimposed perturbation will grow in amplitude.

Having chosen a basic state U and B, the structure of the growing perturbation quantities u', v' and b' is found from two-dimensional, linear, quasi-geostrophic theory. The "channel length" ℓ, i.e., the east-west length of the model domain, is chosen and the theory in the form of a program called 2D-INIT calculates a perturbation pressure field with east-west wavelength ℓ, from which u', v' and b' are calculated. Program 2D-INIT also supplies the growth rate of this perturbation, the fastest growing normal mode solution for the specified ℓ. The channel length is then varied and the process is repeated until the fastest growing mode for any channel length is found. This particular perturbation is known as the "most unstable" mode--this mode, with this wavelength, is the one linear, quasi-geostrophic theory predicts will grow from any infinitesmally small perturbation superimposed upon the basic state.

With the structure of the perturbation known, the perturbation amplitude is chosen so that the maximum value of the perturbation meridional wind component v' is some percentage of the maximum value of the basic state wind U. The basic state and perturbation are then added together. For primitive equation integrations, small corrections are added to the initial wind and temperature fields, based upon the next higher order terms in the Rossby number expansion used in deriving the quasi-geostrophic theory. This "balancing" technique is accomplished by program 3DSTPE; this program produces the actual initial fields, u, v and b. See (1) for more details concerning the basic state and initial conditions.

The initial conditions used previously for experiments have been limited in realism in at least two ways:

1) Since the basic state is independent of x, the initial upper level wind and temperature patterns tend to be too straight in the east-west direction; i.e., no real waves are present in the upper level flow.

2) There are no surface frontal zones present. One often finds them in the atmosphere.

II. Objectives:

As mentioned in section I, the overriding objective of this work, at least as far as its relevance to AFGL is concerned, was to provide a more stringent test than has hitherto been performed of the Shapiro numerical integration filter. This was to be done by integrating more realistic atmospheric simulations than have been done before with the 3DPE model. Specifically, attempts were to be made to find more realistic initial conditions than those discussed in the introduction. Three approaches were attempted:

a) To introduce variations in the zonal (i.e., east-west) direction by finding some initial large amplitude wave pattern. This could be done by superimposing a large amplitude upper level wave upon the zonally independent basic state.

b) To use a channel length not necessarily equal to that associated with the "most unstable" perturbation mode. The structure of the perturbation calculated by 2D-INIT appropriate for the chosen channel length would be used.

c) To attempt to introduce an east-west oriented surface frontal zone into a basic state. It was hoped that an amplifying disturbance would be found to develop along the surface front, thus simulating numerically a classical "polar front cyclone".

Approaches, or objectives b) and c) retained the zonally independent basic state while a) attempted to make the basic state a function of x also.

III. <u>Approaches taken in the research effort</u>:

The more stringent test of the filter would follow from the development of more realistic initial conditions for the 3DPE integrations. In order to accomplish objective a) I planned originally to find by analytic means some basic state that contained some x as well as some y and z dependence. Several attempts along these lines proved futile, due in part to constraints required by the way 3DPE presently is coded and operates. A second approach was then decided upon. I chose a basic state and the appropriate "most unstable" perturbation from my thesis work. For the thesis the initial perturbation amplitude was set to 5%; very small amplitude east-west waves are thus superimposed upon the zonally independent basic state pattern (see 1, figs. 10 and 12). For the experiments done here I retained the zonally independent basic state but I used significantly larger initial perturbation amplitudes: 10%, 25%, 50% and 100%. This forced significant waves to appear in the initial conditions.

The rationale behind this approach was as follows. First, merely increasing the perturbation amplitude without changing the "function of y,z only" constraint upon the basic state seemed the simplest way to proceed. The structure of the "most unstable" perturbation associated with the particular basic state chosen shows a maximum amplitude at jet stream level rather than at the ground (1). This hopefully meant that use of a large amplitude would result in a large amplitude east-west wave at upper levels but still relatively little amplitude in the surface pressure pattern. Finally, note that, upon looking at upper level wind charts, one almost always sees the presence of large amplitude waves before the significant development of surface pressure disturbances. We can therefore consider the appearance of surface cyclones and anticyclones as "forced" by the wave patterns aloft. Thus introducing significant upper wave patterns, with the associated surface pattern (hopefully not too large) would possibly bear some resemblance to realistic atmospheric flow.

The rationale for objective b), the use of a channel length different than that associated with the "most unstable" mode, is the same as that immediately above. An upper wave pattern will force development of a cyclone with a wavelength related to the upper wave. Since the "initial" pattern in the atmosphere almost always appears with a finite amplitude wave of some wavelength, the linear theory prediction of a certain wavelength disturbance appearing--the most unstable disturbance--never comes to pass.

Objective c) was to include a surface frontal zone in the basic state Several attempts with an analytical approach failed and the procedure finally utilized is now explained.

We start with the basic state field of pressure P(y,z) in program 2D-INIT. From this the fields of buoyancy B(y,z) and wind U(y,z) are calculated from $B = P_z$ and $U = -P_y$. In order to get a "realistic looking" frontal zone introduced near the ground, the lowest three of the ten levels of B in the vertical were subjectively (by hand) modified so a "realistic looking" frontal zone appeared in the B field. The new P field could then be calculated from the hydrostatic equation: $B = P_z$ becomes, in vertical finite difference form,

$$\frac{B_k + B_{k+1}}{2} = \frac{P_{k+1} - P_k}{\Delta z}$$

or,

$$P_k = P_{k+1} - \frac{\Delta z}{2}(B_k + B_{k+1}).$$

We know B_k everywhere, i.e., all $k = 1$ to 10, and we know that no change in B_k from level $k = 4$ on up has been made, hence P for $k = 4$ and up is unchanged. So setting $k + 1$ equal to 4 we work downward to get P_k for $k = 3$, 2 and 1. Then knowing P_k everywhere we can get U everywhere.

IV. Results:

The large amplitude wave experiments are described first. All four cases, the 10%, 25%, 50% and 100% amplitude initial conditions, had an east-west domain of integration of 4800 km and a north-south domain of 7200 km, centered at mid latitude (~40°N). All major integrations performed with 3DPE during the summer research used 20 gridpoints east-west, 30 north south and 10 in the vertical, so $\Delta x = \Delta y = 240$ km for the runs described here. This is a relatively coarse horizontal resolution.

In all four cases, the developing cyclone wave, while realistic looking in some ways, is too large scale, covering an east west distance the length of the United States. Atmospheric cyclones tend more to be half this size. The upper level wave pattern did become more pronounced with increasing initial perturbation amplitude, acquiring a more realistic look as was hoped. Unfortunately, the realism of the surface features diminished with increasing initial perturbation amplitude, the starting surface pressure difference between high and low being as large as 37 mb for the 100% case. In addition the surface temperature pattern became more unrealistic as the initial perturbation amplitude increased. Thus the surface patterns had more amplitude than was hoped for, compared to the upper wave pattern, and the 50% and 100% cases effectively were starting out with deep surface cyclones instead of with weak, incipient storms. It would appear that this method of increasing the realism of the initial conditions does not, in general, yield good results.

With respect to providing a good test for the filter, however, the large amplitude experiments were quite successful. The 100% case quickly formed strong surface frontal zones which were maintained by the filter throughout the integration. The other cases produced similar results. The formation and movement of cold, warm and occluded fronts seemed to proceed in a realistic manner with the exception of the warm fronts being too strong compared to the cold fronts as noted in the introduction and as expected for this particular basic state, based upon my thesis work. The filter thus is considered to have "passed with flying colors" and this objective has been successfully met and will no longer be discussed.

Next, the use of a channel length different from that associated with the "most unstable" mode is discussed. A basic state different than the one chosen above was used, with the north-south domain being 3600 km. The "most unstable" mode predicted by 2D-INIT had an east-west wavelength of ~3600 km but a channel length of 2400 km was used. This gave $\Delta x = \Delta y = 120$ km, twice the horizontal resolution of the a) experiments. The cyclone that formed was about half the size of those described above, hence a more realistic size, and it was "shallow" in that little upper level wave activity occurred even as the surface cyclone matured and weakened. Initial perturbation amplitudes of 10% and 25% were run, with similar results. The 25% run is discussed with the aid of the two figures. This run produced a cold front with hardly any warm front, as often occurs in nature. Fig. 1 shows the surface pressure and temperature pattern at the start; Fig. 2 shows these fields for day 3, after the developing cyclone has moved off the eastern edge and back onto the western edge of the domain (which is cyclic in the east-west direction). The surface pressure amplitude has increased from 12 to 23 mb by this time, and the cold front with a lack of warm front is apparent. An unrealistic aspect is the warm region present initially SE of the low center in Fig. 1. This has moved into the low center by day 3 and the filter has reduced its value slightly.

This b) initial state seems to have resulted in a rather realistic cyclone evaluation. A better judgement would come from a comparison of this run and the "most unstable" 3600 km wavelength case, which was not run. A comparison of warm vs cold frontogenesis would be quite interesting (as discussed in section V), so approach b) was suggestive but not conclusive that the wavelength of surface cyclone waves is "forced", i.e., it is not that of the "most unstable" mode predicted by linear theory.

Approach c) was the attempt to introduce the east-west oriented surface frontal zone into the initial conditions. This required the most time and effort and was the least successful, although interesting results did emerge. The basic state was the same as that used for approach b) except that the lowest three levels were modified (see section III) to add the frontal zone. A channel length of 2400 km was chosen here, too, and the perturbation predicted by 2D-INIT for that wavelength--a slowly amplifying disturbance--was used. An initial perturbation of 25% was chosen, but the "balanced" fields produced by 3DSTPE were quite unrealistic, with small scale waves being present parallel to the front. The problem was alleviated somewhat by reducing the initial perturbation amplitude to 10%, but future work with frontal zones in the basic state will require another look at the balancing procedure. The full, three-dimensional integration produced no amplifying "polar front cyclone". In fact the initial perturbation weakened, resulting in a cold frontal trough propagating along toward the ESE with no associated low nor warm front. The filter did not weaken the front as it evolved. This attempt to model a "classical" polar front cyclone must thus be considered a failure although the situation shown in Figs. 1 and 2 can be considered to be somewhat similar to a polar front cyclone.

V. <u>Recommendations</u>:

I feel that the filter needs no further testing with respect to its ability to maintain frontal zones within atmospheric simulations. It has worked well.

With respect to follow on research, I would like to investigate more fully the warm vs cold frontogenesis discussed in section IV, approach b). I would like to repeat the 2400 km integration and compare it to a 3600 km wavelength integration, as mentioned there. The 2D-INIT prediction of perturbation structure for the 3600 km, "most unstable" mode is different from that for the 2400 km case used, the former being a "deep" perturbation with significant wave amplitude at tropopause level while the latter is "shallow".

In addition, the structure of the heat and momentum fluxes, as predicted by 2D-INIT, is quite different for the two perturbations. The evolution of these fluxes should be investigated as it relates to the effect the perturbation has on the surrounding atmosphere.

In order to maintain the same spatial resolution for a 3600 km run, half again as many gridpoints would need to be used as for the 2400 km run--a somewhat large integration. I feel a "mini-grant" is an appropriate vehicle to use for this follow on work. With respect to modeling a polar front cyclone, more thought will be needed before more simulation attempts should be undertaken.

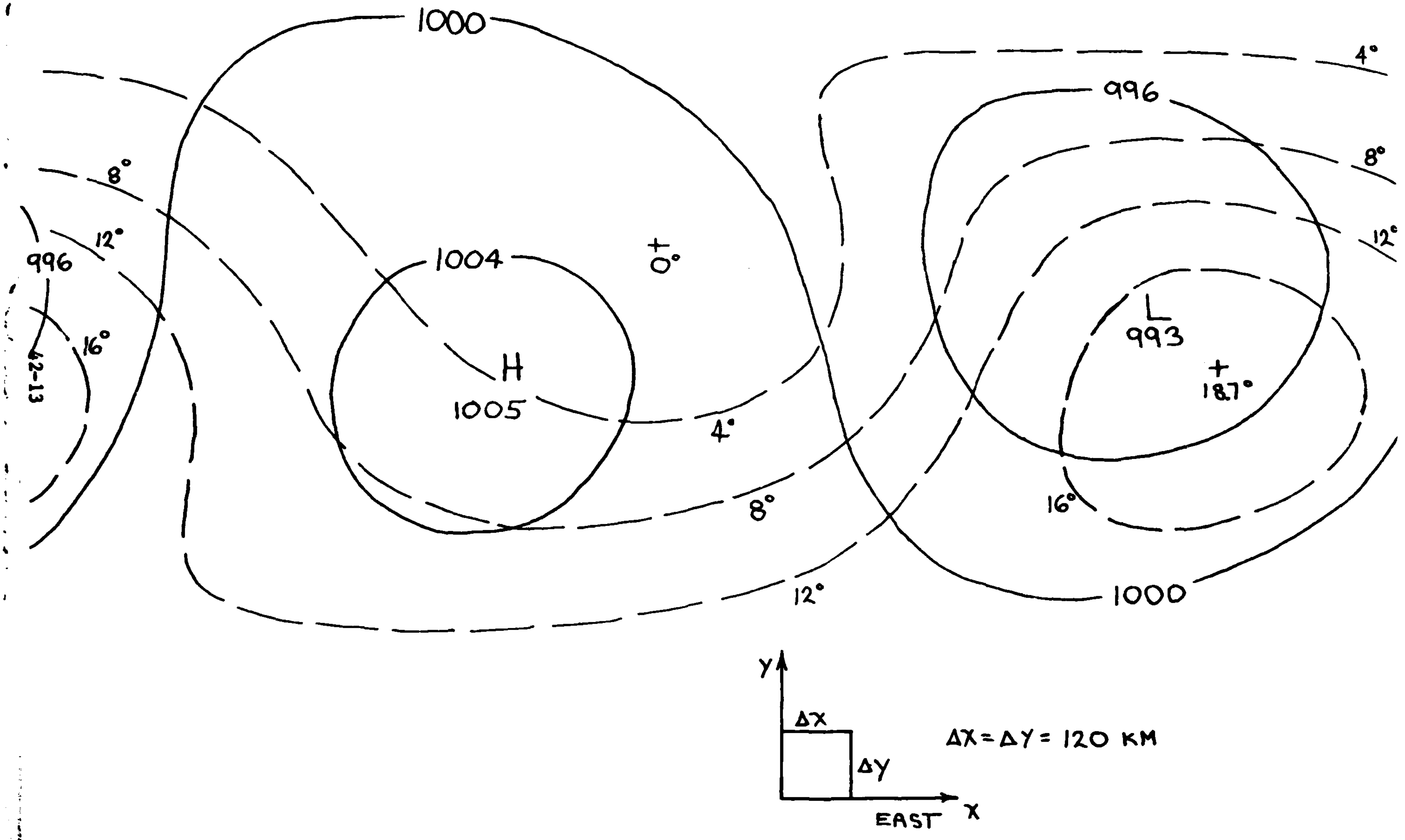

FIG. 1. SURFACE PRESSURE (MILLIBARS) AND TEMPERATURE (°C) AT 0 DAYS.

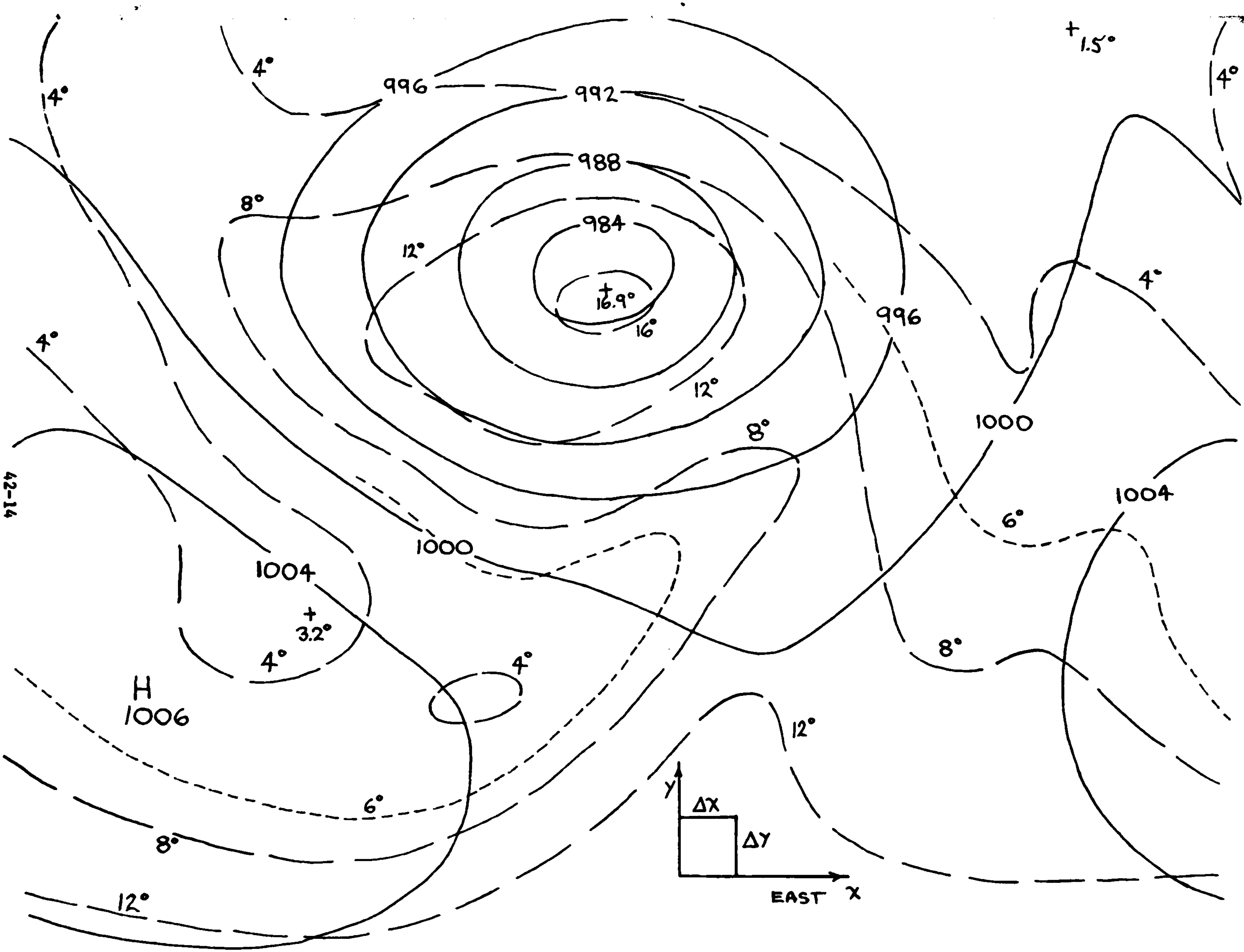

FIG. 2. SAME AS FIG. 1. BUT FOR 3 DAYS.

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